WHITE PAPER

Untreated Highway Runoff in Western Washington

Prepared for

Washington State Department of Transportation

May 2007

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ENVIRONMENTAL
CONSULTANTS

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Untreated Highway Runoff in Western Washington

Prepared for

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May 16, 2007

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Introduction

This white paper identifies pollutants that are present in untreated highway runoff (as measured at edge of pavement and prior to any treatment via natural process and/or engineered systems). Where possible, it also describes typical and worst case concentrations of these pollutants and the key factors that may influence these concentrations based on data compiled from studies in western Washington. Finally, this white paper identifies any significant data gaps, areas of uncertainty, and limitations of the available monitoring data.

This white paper begins with a general overview of the typical pollutants that are present in untreated highway runoff, their primary sources, and the major factors influencing their concentrations. It then provides detailed information on the specific pollutants that are present in highway runoff within western Washington. Finally, major conclusions from this evaluation are presented in the concluding section.

Typical Pollutants in Highway Runoff

Highway runoff contains a variety of pollutants which, if left untreated, can impair water quality and pose a risk to aquatic organisms. Review studies have examined the constituents in highway runoff (e.g., see Barrett et al. 1995a), and several categories of pollutants have been identified as important constituents including: suspended solids, oxygen demand, nutrients, heavy metals, organic compounds, petroleum products, and bacteria. Typical pollutants in highway runoff are shown in Table 1, which also includes the conventional water quality parameters such as conductivity, hardness, and pH.

Table 1. Typical pollutants in highway runoff.

Pollutant Parameter Category	Parameter
Suspended Solids	Total suspended solids
	Volatile suspended solids
Metals	Arsenic
	Cadmium
	Chromium
	Copper
	Iron
	Lead
	Mercury
	Nickel
	Zinc
Nutrients	Ammonia nitrogen
	Nitrate nitrogen
	Total Nitrogen
	Total Kjeldahl nitrogen
	Total Phosphorus
	Orthophosphate phosphorus
Organic Compounds	Polycyclic aromatic hydrocarbons
	Oil and grease
	Total petroleum hydrocarbons
	Pesticides
	Herbicides
Bacteria	Total coliform bacteria
	Fecal coliform bacteria
Oxygen Demand	Biological oxygen demand (5-day)
	Chemical oxygen demand
Conventional Parameters	Sodium (if deicing performed)
	Chloride (if deicing performed)
	pH
	Turbidity
	Conductivity Hardness

Studies of highway runoff usually do not include all of the parameters listed in Table 1. Because of their adverse impacts on aquatic biota, the parameters most frequently monitored are sediments and metals (Portele 1981; Yonge 2002). Total suspended solids and volatile suspended solids are the most common solids parameters measured because toxic organic contaminants and metals are often bound to fine particles. Therefore, concentrations of total suspended solids (TSS) are almost always reported in highway runoff.

Depending on the study, metals are reported as either total metals or dissolved metals, with some studies reporting both. Rarely does a single study measure the entire suite of metals listed in Table 1. The metals most commonly reported in the literature are copper, iron, lead, and zinc (Barrett et al. 1995a, 1998; Kayhanian et al. 2003). In some studies, metals such as nickel, cadmium, and metalloid arsenic were rarely present in detectable concentrations (Barrett et al. 1995b; Kayhanian et al. 2003). In western Washington, the most commonly detected and measured metals are dissolved and total copper and dissolved and total zinc (WSDOT 2006), which tend to be the most bioavailable metals in highway runoff (Preciado and Li 2006).

The nutrients measured in each study vary; however, most studies include at least one form of nitrogen and phosphorus. High nutrient loadings to aquatic systems are a concern because they can stimulate excessive algae growth. As this algae dies off and decomposes, dissolved oxygen concentrations in the water may decrease to levels that are harmful to aquatic organisms. Referred to as *eutrophication*, this process is contributing to water quality problems in some local water bodies (e.g., Hood Canal).

Studies of highway runoff are often designed to provide information related to a specific issue, such as the effects of deicers on the water quality of streams. In this case, the measured parameters might include chloride, sodium, and suspended solids (from sanding). Land use may also dictate the parameters that are measured in a study. In agricultural regions, the pollutants of concern may be pesticides; in a more urban setting, they may be polycyclic aromatic hydrocarbons (PAHs), oil and grease, and diesel fuel. Lastly, agencies may be required to monitor specific pollutants based on conditions specified in their discharge permits.

Sources of Pollutants in Highway Runoff

Sources of highway runoff pollutants have been reviewed and summarized in numerous reports (Barber et al. 2006; Barrett et al. 1995a; Yonge et al. 2002; Young et al. 1996). The sources of pollution can be classified into three general categories: atmospheric deposition, vehicles (including fuels and exhaust emissions); direct and indirect deposition and application (Table 2).

Table 2. General source categories of highway pollutants.

Source Category	Pollutants
Atmospheric deposition	Particulates, nitrogen, phosphorus, metals, PAHs, and PCBs
Vehicles	Particulates, rubber, asbestos, metals, sulfates, bromide, petroleum, and PAHs
Direct and indirect deposition and application	Particulates, nitrogen, phosphorus, metals, sodium, chloride, sulfates, petroleum, pesticides, and pathogens

PAHS = polycyclic aromatic hydrocarbons.
PCBs = polychlorinated biphenyls.

Atmospheric deposition refers to substances that are deposited on land surfaces from the air. This deposition can contain pollutants such as nutrients, particulates, PAHs, PCBs, and heavy metals. Deposition and be classified as dry deposition, when pollutants settle out from the surrounding air, and through wet deposition, which carries pollutants from the sky through precipitation. Metals are emitted from near and distant industrial sources. Incomplete combustion of fossil fuels contributes nutrients and PAHs in deposition materials. PCBs primarily originate from historic usage of these compounds in industrial applications.

Most pollutants associated with vehicles originate from engine wear and exhaust, lubricants, rusting, and tire wear. Brake pad wear is a source of copper and zinc, which are the metals most commonly found in highway runoff; tires contain zinc; some older brake contain lead; and wheel-balance weights are made primarily of lead.

The direct and indirect deposition and application category includes right-of-way maintenance (e.g., the application of fertilizers, herbicides, and pesticides), roadway maintenance (e.g., deicing and road repairs), and animal wastes. Fertilizers and herbicides in runoff usually originate from their application on median strips and right-of-ways (Yonge et al. 2002). Animal wastes include the direct deposition of bird and other wildlife feces, decomposition of road kill, and losses during the transport of livestock and livestock wastes (EWGCC 2000).

Table 3 presents a detailed list of pollutants and their sources compiled from existing reports (Barber et al. 2006; EWGCC 2000; Kobriger 1984; TRB 2006; Yonge et al. 2002).

Table 3. Specific sources of pollutants in highway runoff[a].

Pollutant	Source
Particulates (solids)	Pavement wear, vehicles, atmospheric deposition, maintenance activities, snow/ice control, sediment disturbance
Rubber	Tire wear
Asbestos [b]	Clutch and brake lining
Lead	Tire wear, atmospheric deposition, bearing wear
Zinc	Motor oil and grease, tire wear
Iron	Auto body rust, highway structures (bridges, guardrails), moving engine parts
Copper	Engine wear, brake lining wear, metal plating, insecticides and fungicides
Cadmium	Tire wear, lubricants
Chromium	Metal plating, brake lining wear, moving engine parts
Nickel	Lubrication oil, diesel fuel and gasoline, metal plating, asphalt paving, brake lining wear
Manganese	Moving engine parts
Nitrogen and phosphorus	Atmospheric deposition, fertilizer applications, dead plant material, road-kill, sediments, exhaust
Sodium and chloride	Deicing salts
Sulfates	Fuels, deicing salts
Petroleum	Spills, leaks, hydraulic fluids, asphalt surface
PAHs	Exhaust
Pesticides, herbicides	Atmospheric deposition, spraying of rights-of-way, soils
PCBs	Atmospheric deposition
Bacteria	Soil litter, wildlife waste, road-kill, trucks hauling livestock waste

PAHs = polycyclic aromatic hydrocarbons.
PCBs = polychlorinated biphenyls.
[a] Data sources: Barber et al. 2006; EWGCC 2000; Kobriger 1984; TRB 2006; Yonge et al. 2002.
[b] No mineral asbestos has been identified in runoff, but products of asbestos breakdown have been observed (EWGCC 2000).

Factors Affecting Pollutants in Highway Runoff

Many factors may affect the type and amount of pollution in highway runoff:

- **Traffic:** amount of traffic (annual average daily traffic), type of traffic (commuter, industrial, or construction), number of vehicles traveling during a storm, number of vehicles traveled before a storm, air turbulence caused by vehicles, traffic congestion (resulting in braking), and vehicle speed

- **Precipitation**: storm event duration, storm event precipitation amount, antecedent dry period, and average or maximum hourly rainfall intensity during the storm

- **Road conditions and maintenance**: deicing, sanding, snow plowing, weed control, highway surface material type (concrete versus asphalt; conventional versus porous), and presence of rumble strips, guardrails, or wire barriers

- **Land use**: urban versus rural and proximity to industry.

In general, these factors will interact in complex ways to determine what types of pollutants are present in highway runoff and their associated concentrations at any given point during a storm event. These factors and related interactions are discussed in more detail within the section that follows based on data obtained from local and national studies for specific categories of pollutants. However, it should be noted that few local studies have been performed to investigate this research question. Furthermore, the results obtained from national studies may not be equally relevant in western Washington due to differences in rainfall patterns, land uses, highway maintenance practices, and other considerations. Therefore, it should be recognized that there is a considerable amount of uncertainty surrounding the information presented herein on this topic.

One particularly important factor that may influence pollutant concentrations in highway runoff is the buildup of solids and other pollutants on pavement and in gutters between storms. The subsequent mobilization of this material during storm events can cause the runoff to display first flush characteristics, meaning runoff in the early stages of the storm has the highest concentrations and a majority of the pollutant load. As a result, many agencies focus on sampling and treating the first 0.5 inches of accumulated precipitation during a storm event.

However, some researchers (Mar et al. 1982) have postulated that the first flush phenomenon does not strongly influence pollutants in runoff in the Pacific Northwest for two reasons. First, rainfall in western Washington is of low intensity and longer duration than rainfall in the rest of the country. As a result, accumulated solids are gradually carried away from the highway. Second, traffic-generated winds are effective in removing debris from highways. Furthermore, naturally occurring high winds in some parts of Washington can also effectively remove solids (and therefore sediment-bound pollutants) from highways (Lancaster 2005). It should also be noted that most first flush data are from samples collected in parking lots and on residential streets, and may not be reflective of conditions on highways in western Washington (Mar et al. 1982). Nonetheless, a first flush phenomena has been observed in western Washington highway runoff, although it may be less common in this region relative to other parts of the country.

Pollutants in Western Washington Highway Runoff

This section of the report characterizes pollutants in highway runoff for western Washington based on data that were compiled from 11 studies and 35 different monitoring locations within the region. The specific parameters that have been measured in association with each study are listed in Table 4. Most of the associated monitoring locations are in the Seattle vicinity, with two locations in Vancouver, Washington, and one location near Snoqualmie Pass. Appendix A provides more detailed information on the monitoring that was conducted at each of these locations including the number of sampled storm events, the type of sample collected (e.g., grab, flow-weighted composite), and period of sampling.

Highway runoff in this region has been studied for decades. Earlier studies referenced in this report examined the general characteristics of highway runoff (Asplund et al. 1980) and included specific studies of trace organics in the Seattle area (Zawlocki 1981). More recently, runoff data have been collected to monitor the effectiveness of highway runoff best management practices in the region (see WSDOT 2006; Herrera 2007). Out of the 35 monitoring locations that were used in this report to characterize highway runoff in western Washington, data from 27 of these locations were collected from 1995 to the present, while data from eight locations were collected prior to 1990. However, with the exception of lead, data from the older studies were generally comparable to the more recent data. Therefore, older and more recent data for western Washington were generally pooled in this report to characterize untreated highway runoff. In the case of lead, which was historically present at much higher concentrations prior to the elimination of leaded gasoline, only the most recent data were used to characterize highway runoff in this report.

Where applicable, the central tendency, variance, and range for each pollutant in highway runoff are characterized within this section using tabular and graphical representations of the data. The tabular representations (see Table 5, Appendix B) present basic summary statistics for each pollutant based on data compiled from the available studies in the region. The graphical representations consist of box plots showing the following summary statistics for each pollutant based on data obtained from these same studies: minimum, 25th percentile, median, 75th percentile, and maximum. An example box plot is provided in Figure 1 to show how each of these summary statistics is depicted. Summary statistics for individual parameters in both the tabular and graphical representations of the data were computed based on the mean value from individual monitoring locations in each study as opposed to the raw data.

In order to provide some frame of reference for interpreting highway runoff pollutant concentrations in western Washington, commonly cited (Barrett et al. 1995a, 1998; Yonge et al. 2000, 2002) national data are also presented herein for reference (see Table 5). These data have been adapted from Barrett et al. (1995a) and include data from a national survey that was compiled by Driscoll et al (1990). However, because pollutant concentrations in highway runoff can be influenced by rainfall patterns, surrounding land uses, highway maintenance practices, and other regional factors, these data are provided for comparison purposes only and are not meant to be representative of conditions in western Washington.

Table 4. Parameters measured in western Washington highway runoff.

Parameter	Reference
Suspended Solids	
Total suspended solids	King County (2006); WSDOT (2006); Driscoll et al. (1990); Taylor (2002); Yonge et al. (2002); Portele (1981); Zawlocki (1981); Dalseg and Farris (1970); Sylvester and DeWalle (1972); St. John and Horner (1997)
Volatile suspended solids	Driscoll et al. (1990); Yonge et al. (2002); Zawlocki (1981)
Metals	
Copper (total)	King County (2006); WSDOT (2006); Driscoll et al. (1990); Herrera (2005); Yonge et al. (2002); Portele (1981); Zawlocki (1981); St. John and Horner (1997)
Copper (dissolved)	WSDOT (2006); Herrera (2005); Yonge et al. (2002); Portele (1981)
Zinc (total)	WSDOT (2006); Driscoll et al. (1990); Taylor (2002); Herrera (2005); Yonge et al. (2002); Portele (1981); Zawlocki (1981); St. John and Horner (1997)
Zinc (dissolved)	WSDOT (2006); Taylor (2002); Herrera (2005); Yonge et al. (2002); Portele (1981)
Lead (total)	King County (2006); Driscoll et al. (1990); Yonge et al. (2002); Zawlocki (1981); Portele (1981); Dalseg and Farris (1970); St. John and Horner (1997)
Lead (dissolved)	Yonge et al. (2002); Portele (1981)
Cadmium (total)	King County (2006); Yonge et al. (2002); St. John and Horner (1997)
Antimony	King County (2006); St. John and Horner (1997)
Arsenic	King County (2006); St. John and Horner (1997)
Barium	King County (2006); St. John and Horner (1997)
Chromium	King County (2006); St. John and Horner (1997)
Cobalt	King County (2006); St. John and Horner (1997)
Molybdenum	King County (2006); St. John and Horner (1997)
Mercury	King County (2006)
Nickel	King County (2006); St. John and Horner (1997)
Vanadium	King County (2006); St. John and Horner (1997)
Nutrients	
Total organic carbon	King County (2006); Driscoll et al. (1990); Zawlocki (1981)
Nitrate+nitrite	King County (2006); Driscoll et al. (1990); Yonge et al. (2002); Portele (1981); Zawlocki (1981); Sylvester and DeWalle (1972)
Ammonia	King County (2006); Yonge et al. (2002)

Table 4 (continued). Parameters measured in western Washington highway runoff.

Parameter	Reference
Nutrients (continued)	
Total Kjeldahl nitrogen	Driscoll et al. (1990); Yonge et al. (2002)
Orthophosphate-phosphorus	King County (2006); Driscoll et al. (1990); Taylor (2002); Yonge et al. (2002); Portele (1981); Sylvester and DeWalle (1972); St. John and Horner (1997)
Total nitrogen	King County (2006); Portele (1981); Dalseg and Farris (1970); Sylvester and DeWalle (1972)
Total phosphorus	King County (2006); WSDOT (2006); Taylor (2002); Yonge et al. (2002); Portele (1981); Zawlocki (1981); Dalseg and Farris (1970); Sylvester and DeWalle (1972); St. John and Horner (1997)
Organic Compounds	
Various PAHs	King County (2006); Yonge et al. (2002)
TPH-diesel/oil	Herrera (2007), WSDOT (2006)
Oil and grease	Zawlocki (1981); Dalseg and Farris (1970); Sylvester and DeWalle (1972); St. John and Horner (1997)
Other organic compounds	King County (2006) ; St. John and Horner (1997); Zawlocki (1981)
Bacteria	
Total coliform bacteria	Sylvester and DeWalle (1972)
Fecal coliform	Herrera (2007); WSDOT (2006), King County (2006); Sylvester and DeWalle (1972)
E. coli bacteria	King County (2006), WSDOT (2006)
Oxygen Demand	
Chemical oxygen demand	Driscoll et al. (1990); Yonge et al. (2002); Zawlocki (1981); Dalseg and Farris (1970); Sylvester and DeWalle (1972); St. John and Horner (1997)
Biological oxygen demand (5-day)	Portele (1981); Dalseg and Farris (1970); St. John and Horner (1997)
Conventionals	
Hardness	King County (2006); WSDOT (2006); Taylor (2002); St. John and Horner (1997)
Alkalinity	Yonge et al. (2002); Sylvester and DeWalle (1972); St. John and Horner (1997)
Turbidity	Taylor (2002); Sylvester and DeWalle (1972); St. John and Horner (1997)
pH	Portele (1981); Taylor (2002); Sylvester and DeWalle (1972)
Specific Conductivity	St. John and Horner (1997)

PAHs = polycyclic aromatic hydrocarbons.
TPH = total petroleum hydrocarbons.

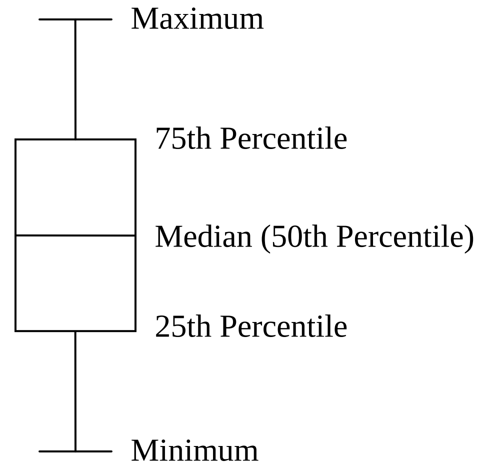

Figure 1. Sample box plot showing the minimum, 25th percentile, median, 75th percentile, and maximum of the data.

Finally, it should be emphasized that the specific intent of this analysis is to characterize highway runoff concentrations at edge of pavement. In most cases, highway runoff does not discharge directly to a receiving water after leaving the pavement; rather, it traverses slopes and ditches located adjacent to the highway. In the process, some treatment of this runoff likely occurs through naturally occurring processes (e.g., filtration and infiltration). Alternatively, highway runoff is typically collected at edge of pavement and routed to an engineered treatment system. (Note that a subsequent white paper to be prepared in connection with this project will characterize pollutant concentrations in highway runoff after treatment in these systems.) Based on these considerations, the pollutant concentrations for highway runoff that are presented herein should not be considered representative of the pollutant concentrations at the point of discharge for this runoff to receiving waters. Furthermore, all comparisons of these data to applicable water quality standards are made for informational purposes only and should not be construed to represent actual conditions within receiving waters.

The discussion within this section is organized under separate subsections for the following major categories of pollutants: suspended solids, metals, nutrients, organic compounds, bacteria, oxygen demand, and conventional water quality parameters. In general, each subsection identifies the potential sources for each pollutant and the factors that may influence its presence in highway runoff. Concentrations of each pollutant in highway runoff are then characterized based on summary statistics that were computed using data obtained from the studies in western Washington (see Table 4; Appendix A). As necessary, the tabular and graphical representations of the data described above are provided in each subsection to facilitate comparisons of these summary statistics. Summary statistics for each pollutant are also compiled separately in Appendix B based on the data from western Washington.

Suspended Solids

Sources of Suspended Solids in Highway Runoff

Solids entrained in runoff originate from materials that have collected on the road surface, rust and wear of vehicles, sand applied to roads to improve vehicle traction on snow and ice, erosion of the surrounding landscape, road particles (from the roadway surface itself), and atmospheric deposition (Bent et al. 2001; Barrett et al. 1995a). Suspended solids can also include plant and leaf materials from the grooming of median strips and other road maintenance activities (Bent et al. 2001; Irish et al. 1998), and natural senescence. In Washington, it has been shown that solids can be indirectly deposited onto the roadway by vehicles that carry various solid materials from construction sites, parking lots, and dirt roads (Asplund et al. 1980).

Many constituents in highway runoff are associated (bound) with solids, including metals, bacteria, polycyclic aromatic hydrocarbons (PAHs), other organic compounds, total organic carbon, and chemical oxygen demand (Bent et al. 2001; Barrett et al. 1995a; Driscoll et al. 1990; Irish et al. 1998; EWGCC 2000). As a result, decreasing the amount of suspended solids in highway runoff may reduce loading from these other pollutants and lessens the degradation of water quality in the receiving waters. Suspended solids are typically measured as total suspended solids (TSS) and volatile suspended solids (VSS), which is a measure of the organic matter in suspended solids.

Factors Affecting Suspended Solids in Highway Runoff

In general, both national and local studies have shown that the amount of solids in highway runoff can be controlled by precipitation and other factors that influence the availability of transportable material. Therefore, conditions such as the antecedent dry period and the intensity of the previous storm event have been identified as important parameters that correlate with total suspended solids in runoff from highways (Irish et al. 1998; Barber et al. 1995a; Sansalone et al. 1998). However, rainfall intensity also plays an important role. If a storm is more intense, the ability to suspend solids is greater (Bent et al. 2001; Barrett et al. 1995a; Horner et al. 1990).

Suspended solids also exhibit first flush characteristics in most studies, but sometimes a more complex behavior is observed. For example, some national runoff studies have shown that the concentration of TSS increases during a first flush but then flattens out at an elevated level throughout the remainder of the storm (Barrett et al. 1998). Other national studies show a first flush effect for TSS and VSS with the flushing signal being weaker for smaller storms, indicating that rainfall intensity may influence the degree of a first flush signal (Sansalone et al. 1998).

Other factors that influence the availability of transportable solids include traffic volume, road maintenance activities, surrounding land uses, and seasonal differences. In several local and national studies, average daily traffic (ADT) alone was not strongly correlated with TSS (Driscoll et al. 1990; Horner et al. 1979; Kayhanian et al. 2003). However, Kayhanian et al. (2003) found that annual ADT, in conjunction with factors associated with pollutant buildup and wash off (e.g., antecedent dry period), does correlate with most highway runoff pollutants, including TSS.

In Washington, studies have shown that the number of vehicles during a storm (VDS) may be a more important influence on suspended solids than ADT (Asplund et al. 1980; Chui 1981). For example, during a 5-year study of TSS loads in Washington state, a linear regression of cumulative TSS load versus cumulative VDS showed a strong relationship (Asplund et al. 1980).

As noted above, antecedent dry period has also been shown to influence TSS concentrations (Irish et al. 1998). However, there is evidence that vehicle turbulence can actually reduce the amount of solids that has collected on highway surfaces between storm events (Kerri et al. 1985). In western Washington, Wang et al. (1982) showed that a large fraction of solids is deposited within 15 meters of the roadway. Mar et al. (1982) discuss how even after the eruption of Mount St. Helens, wind from vehicles was very effective at removing large amounts of ash that had been deposited in the region. Furthermore, they discuss additional factors controlling solids loading on highways: width of distress lanes, height of curbs, and speed of traffic. These additional factors can sometimes result in a weak correlation between TSS and the amount of traffic or the number of dry days between storms.

Road maintenance activities such as grass cutting, guardrail repair, bridge washing, and application of sand for snow and ice can also greatly influence TSS loads (Irish et al. 1998). Furthermore, the use of studded tires and the use of sand for deicing can increase solids loading during winter in some areas (Gupta et al. 1981). However, in a local study, Horner et al. (1979) found that increases in solids loading due to construction in the spring can outweigh increases due to sanding in the winter. Nonetheless, these studies indicate a seasonal effect on TSS in runoff. In addition, the particle size distribution of the solids is important. Studies have shown that particles in smaller size fractions (e.g., clay in the 2-8 micron range) are moved easily during storm events, whereas coarser particles are not (Sansalone et al. 1998).

TSS in highway runoff has been attributed to road sanding activities in Washington state. Yonge et al. (2002) found that TSS in runoff was lower in Vancouver, Washington than in Spokane, Washington, as a result of fewer snow storms and, therefore, less sanding of the roads in western Washington than in eastern Washington. Over 50 percent of the solids loading from 10 sites in Washington were traced back to sanding operations (Asplund et al. 1980).

In a study by Driscoll et al. (1990), surrounding land use was reported to be one of the more important factors affecting highway runoff quality in western Washington. In general, this study showed that concentrations of suspended solids and associated pollutants tended to be higher near urban areas. In a national study, Gupta et al. (1981) also found higher amounts of atmospheric dust fall on highways near urban areas. Furthermore, the surrounding topography (slope, amount of vegetation, and soil type) will affect the amount of suspended solids that can be transported to highways and subsequently entrained in runoff.

Finally, the volume of runoff from a storm and the type of highway surface (e.g., concrete versus asphalt) have been studied, but the results were inconclusive, indicating these are not strong factors in terms of their influence on solids concentrations in highway runoff (Barrett et al. 1995).

Concentrations of Suspended Solids in Highway Runoff

TSS and VSS data from western Washington are shown in Figure 2. These data include mean concentrations of TSS from 27 sites and mean concentrations of VSS from five sites. Mean concentrations of TSS range from 3 to 295 milligrams per liter (mg/L) (with a median concentration of 93 mg/L) in western Washington and were less than the range reported in the national data (Table 5). (Additional summary statistics for this parameter are provided in Appendix B.) The TSS data from western Washington include data from samples collected after a sanding event in Woodinville. During this storm event, TSS concentrations increased to more than 900 mg/L (St. John and Horner 1997), demonstrating that road sanding practices can greatly influence pollutant runoff from highways in Washington state. High concentrations associated with sanding events likely represent the worst-case scenario for this parameter.

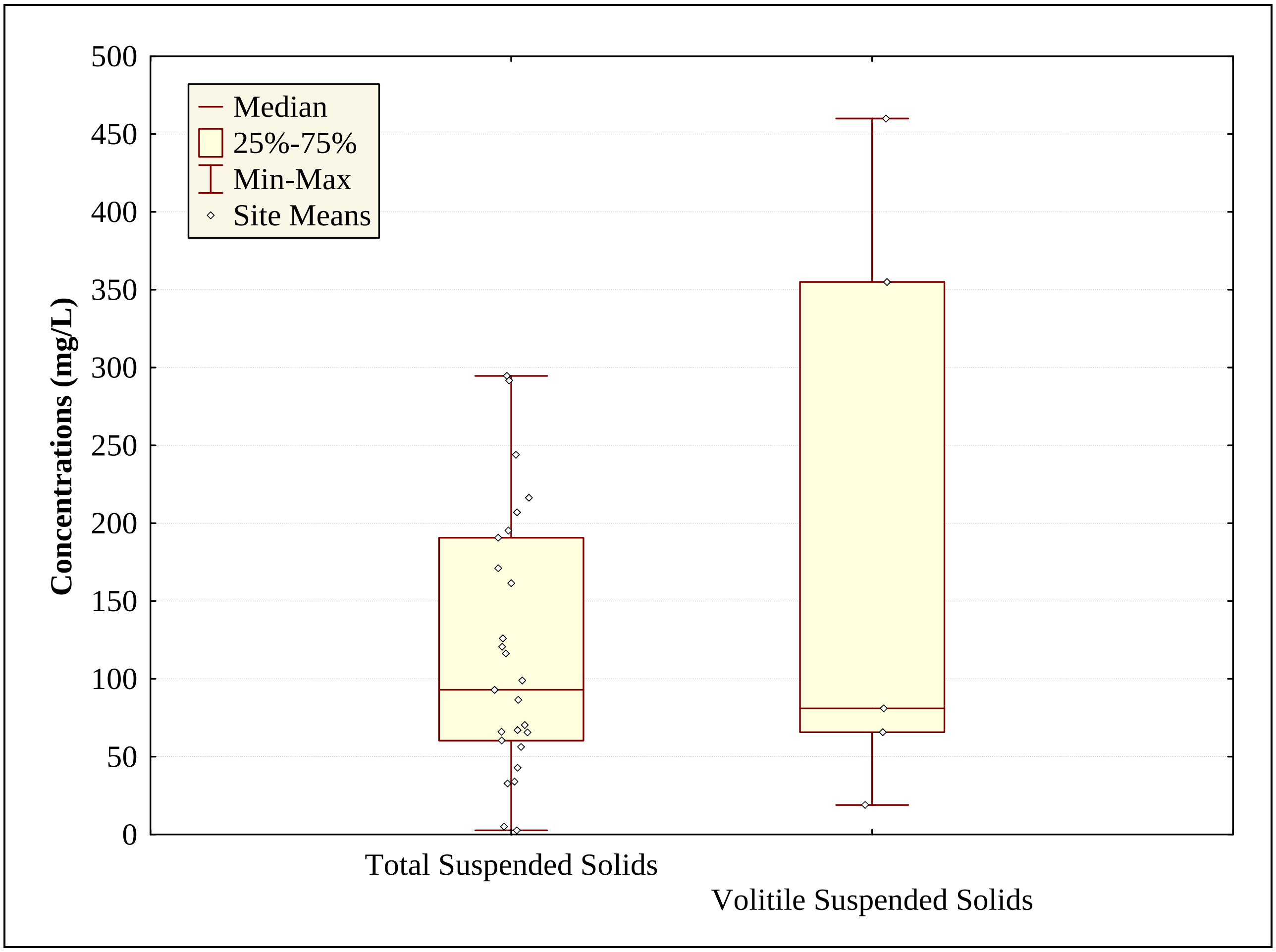

Figure 2. Mean concentrations of suspended solids reported for highway runoff monitoring sites in western Washington.

Mean VSS concentrations range from 19 to 460 mg/L (with a median concentration of 81 mg/L) in western Washington and were much greater than the range reported in the national data (Table 5). (Additional summary statistics for this parameter are provided in Appendix B.)

Table 5. Constituents in highway runoff: comparison of site mean concentrations from data in western Washington to national data.

Constituent	Western Washington Sites [a]	National Data [b]
Solids (mg/L)		
Total	No data	437 to 1,147
Dissolved	No data	356
Suspended	3 to 295 (27)	45 to 798
Volatile (dissolved)	No data	131
Volatile (suspended)	19 to 460 (5)	4.3 to 79
Volatile (total)	No data	57 to 242
Metals, total (μg/L)		
Antimony	1.2 to 8.7 (2)	Not reported
Arsenic	2.2 to 2.6 (2)	58
Barium	81 to 84 (2)	Not reported
Chromium	7.5 to 18 (2)	Not detected to 40
Cadmium	0.9 to 2.8 (2)	Not detected to 40
Cobalt	1.9 to 4.4 (2)	Not reported
Copper	4.6 to 72 (29)	22 to 7,033
Iron	No data	2,429 to 10,300
Lead	24 to 1,065 (10)	73 to 1,780
Lead[c]	24 to 61 (3)	73 to 1,780
Magnesium	No data	1,062
Mercury	0.02 (1)	3.22
Molybdenum	1.5 to 9.5 (2)	Not reported
Nickel	8.6 to 12.9 (2)	53
Vanadium	6.3 to 14.8 (2)	Not reported
Zinc	26 to 394 (29)	56 to 929
Metals, dissolved (μg/L)		
Copper	3.1 to 18.1 (21)	Not reported
Lead	1.0 to 3.2 (2)	Not reported
Lead[c]	3.2 (1)	Not reported
Zinc	13 to 134 (22)	Not reported
Nutrients (mg/L)		
Ammonia nitrogen	1.0 to 2.7 (2)	0.07 to 0.22
Nitrite nitrogen	No data	0.013 to 0.25
Nitrate nitrogen	No data	0.306 to 1.4
Nitrite+nitrate nitrogen	0.51 to 3.0 (6)	0.15 to 1.636
Organic nitrogen	No data	0.965 to 2.3
Total Kjeldahl nitrogen	0.38 to 3.4 (6)	0.335 to 55.0
Total nitrogen	0.78 to 21.7 (2)	4.1
Orthophosphate phosphorus	0.01 to 0.42 (9)	Not reported
Total phosphorus	0.03 to 0.57 (24)	0.113 to 0.998

Table 5 (continued). Constituents in highway runoff: comparison of site mean concentrations from data in western Washington to national data.

Constituent	Western Washington Sites [a]	National Data [b]
Organic Compounds (mg/L)		
TPH-oil	0.42 to 7.9 (12)	Not reported
TPH-diesel	Not detected to 2.75 (8)	Not reported
Oil and grease	11.8 to 187 (4)	2.7 to 27
Bacteria		
Total coliform bacteria (CFU/100 mL)	9,350 (1)	570 to 6,200
Fecal coliform bacteria (CFU/100 mL)	35 to 11,775 (16)	50 to 590
E. coli bacteria (CFU/100 mL)	130 to 1,670 (3)	Not reported
Oxygen Demand (mg/L)		
Chemical oxygen demand	32 to 1377 (11)	14.7 to 272
Biological oxygen demand (5-day)	9.5 to 71 (2)	12.7 to 37
Conventionals		
pH	5.8 to 6.8 (5)	7.1 to 7.2
Specific conductivity (µS at 25 °C)	71.6 (1)	337 to 500
Total organic carbon (mg/L)	2.0 to 139.0 (8)	24 to 77
Turbidity (NTU)	16.3 to 86.7 (3)	19
Hardness (mg/L as $CaCO_3$)	11.1 to 86.1 (19)	Not reported
Alkalinity (mg/L as $CaCO_3$)	19.3 to 23.4 (2)	Not reported

°C = degrees Celsius.
CFU = colony-forming units.
µS = microsiemens.
mL = milliliters.
NTU = nephelometric turbidity units.
TPH = total petroleum hydrocarbons.
[a] Number in the parenthesis represents the number of sites contributing to the range in mean concentration.
[b] Source: Driscoll et al. (1990); Barrett et al (1995a). Number of sites reporting data are not available.
[c] Summary statistics for lead are calculated using only data that were collected after 1990.

Metals

Sources of Metals in Highway Runoff

The primary sources of metals from vehicles are friction in engine and suspension systems, brake pad and tire wear, and rust and corrosion (Kearfott et al. 2005; Barrett et al. 1995a; Lancaster 2005). Metals have also been linked to plating on guardrails (Lancaster 2005), vehicle emissions, and impurities in deicing salts (Barrett et al. 1995a). In addition, the presence of rumble strips can aid in dislodging metals and rust from vehicles through increased vibration (Lancaster 2005). Another indirect source of metals in runoff is suspended solids. In particular, several nationwide studies have shown that concentrations of zinc, copper, and chromium correlate well with TSS concentrations (Kearfott et al. 2005; Kayhanian et al. 2003). In the Pacific Northwest, concentrations of metals are often strongly correlated with TSS concentrations (Chui 1981; Preciado and Li 2006), and in studies where both dissolved and total metals are reported, a large fraction of total metals is associated with particles (Portele 1981). Finally, atmospheric deposition can be an important source for some metals in highway runoff.

Factors Affecting Metals in Highway Runoff

Because of the strong correlation between TSS and metals (Chui 1981; Preciado and Li 2006), factors that affect TSS concentrations also apply to metals. For example, concentrations of metals do not correlate well with ADT alone (Driscoll et al. 1990; Horner et al. 1979; Kayhanian et al. 2003), and VDS may be a better predictor (Barrett et al. 1995a; Irish et al. 1998; Kayhanian et al. 2003). During storms, the spray from tires can wash off solids and metals from cars and deposit them onto the road; this spray is a function of vehicle speed (Lancaster 2005). Furthermore, the particle size of the suspended solids is important. Metals are most associated with finer particles; therefore, they are moved more easily during storms (Lancaster 2005; Sansalone et al. 1998). As a result, rainfall intensity can affect metals loadings in runoff.

In national studies, the length of the dry period before a storm has also been shown to correlate well with the concentrations of some metals (dissolved lead, total lead, and dissolved copper); however, concentrations of other metals (dissolved cadmium, total cadmium, total copper, dissolved and total zinc) did not show a strong correlation with the antecedent dry period (Barrett et al. 1995a; Kerri et al. 1985). These differing results probably stem from several site-specific and/or metal-specific factors that can influence metal accumulation on highway surfaces during the antecedent dry period. In general, metals are typically removed from the roadway in runoff during frequent storms with short antecedent dry periods. However, both national and local studies have shown that with increasing antecedent dry periods, other factors such as atmospheric deposition, air turbulence (due to wind and vehicles), and volatilization/oxidation can reduce the correlation between metal concentrations in runoff and the length of the antecedent dry period (Barrett et al. 1995a; Lancaster 2005; Mar et al. 1982; Wang et al. 1982). In particular, it has been shown that vehicle generated wind can reduce the amount of metals on highways. As an example, Hewitt and Rashed (1990) showed that less than 10 percent of the lead emitted by vehicles was found in runoff, with the remainder being transported away from the road through other mechanisms. Presumably, other metals besides lead are similarly transported by these mechanisms.

Metals also may display first flush characteristics, but each metal species may behave differently depending on what forms are present (e.g., dissolved versus particulate-bound). For example, while a first flush phenomenon is fairly common for dissolved metals, it is observed less frequently for particulate-bound metals because rainfall intensity is an important factor influencing this occurrence (Sansalone et al. 1998). In explaining these differences, Sansalone et al. (1998) describe how there is flow-driven (dissolved) versus transport-driven (particulate) first flush behavior during storms. However, most metals are associated with fine particulates and thus, particulate-bound metals may exhibit first flush behavior on occasion. In general, Sansalone and Buchberger (1997) found that the following dissolved metals have a propensity for first flush behavior in order from greatest to least: cadmium, zinc, copper, and lead. Similarly, the following particulate metals also have a propensity for first flush behavior in order from greatest to least: copper, zinc, lead, and cadmium.

In one local study, Yonge et al. (2002) examined first flush behavior for metals in relation to the different rainfall patterns for Spokane and Vancouver, Washington. For the Vancouver site, first flush behavior was minimal to nonexistent for metals because of the small, frequent rain events that are common for marine-influenced weather. In Spokane, first flush behavior was observed during the majority of winter storms for total metals but not dissolved metals, while the presence of first flush patterns was random during the remainder of the year. Yonge et al. (2002) also observed a definitive "seasonal" first flush event at the Vancouver site for a storm event in June that followed an extended dry period. No first flush characteristics were observed for subsequent storms having shorter antecedent dry periods at the Vancouver site. Yonge et al. (2002) showed the propensity for first flush behavior for both dissolved and particulate metals was in the following order from greatest to least: lead, zinc, copper, and cadmium.

In a detailed study of pollutant runoff in Texas, Irish et al. (1998) found that specific metals were affected differently by traffic and precipitation. More specifically, the following conclusions were drawn from the data:

- Copper and lead were influenced most by traffic, including VDS and the antecedent dry period.
- Iron was influenced by the antecedent dry period, but the numbers of vehicles during storms or between storms were not important influences on this parameter.
- Zinc concentrations correlated best with the dry period traffic count and runoff characteristics of the preceding storm event.

However, it is unclear whether some or all of these conclusions apply to western Washington given the differing precipitation patterns between the two regions.

In general, the behavior of specific metal species in response to the influence of traffic, precipitation, and other factors is difficult to predict due to their complex chemistries in the environment. For example, most metals are found in particulate form, but many factors (e.g., pH, particle size, hardness, and organic content of solids) affect the form of metals (dissolved or particulate) (Barber et al. 2006; Lancaster 2005). As a result, the concentration ranges for the total and dissolved metals in runoff are highly variable (Barber et al. 2006). This distinction is important because dissolved metals are more toxic to aquatic organisms (Barber et al. 2006), and they often have greater bioavailability. Preciado and Li (2006) showed that zinc, copper, and manganese were the metals with the most bioavailability in highway runoff in Vancouver, British Columbia.

Studies in western Washington have shown that only a small percentage of the total quantity of metals that are deposited on highway surfaces are actually entrained in runoff because most of the metals are bound to solids and consequently blown away from the roadway by vehicle-generated winds (Mar et al. 1982). Metals blown into the surrounding landscape have low mobility on well-vegetated surfaces, whereas bare ground (mud or concrete) does not retain metals, resulting in higher concentrations in runoff (Wang et al. 1982). The chemistry of stormwater runoff influences the mobility of metals. At a pH less than 5, metals can be leached from soils, but at a pH greater than 5, they tend to remain immobile (Mar et al. 1982). These observations suggest that vegetation and soil conditions in highway right-of-ways may be very important for controlling metals loadings in highway runoff. In addition, proximity to industry has been shown to increase metal concentrations in runoff. For example, Chui (1981) observed high zinc concentrations in runoff from a highway located near a smelter.

Concentrations of Metals in Highway Runoff

As shown in Table 5 and Appendix B, a wide range of metals have been measured in highway runoff in western Washington. However, copper and zinc have generally been measured most often in monitoring studies (Figure 3), with a majority of these data coming from recent WSDOT sites (WSDOT 2006; Herrera 2007). Results from this monitoring show that copper and zinc (both total and dissolved) are very common in highway runoff, often detected in more than 98 percent of the collected samples. In general, concentrations of particulate metals (i.e., total minus dissolved) were much higher than dissolved metals for copper and zinc. Total and dissolved metals concentrations were higher for zinc compared to copper. The concentrations of total copper and zinc in western Washington are lower than the ranges reported in the national data (Table 5). (Concentrations of dissolved metals were not available in the national data used for this evaluation.)

Based on the mean values from monitoring locations in western Washington, concentrations of total copper range from 4.6 to 72 micrograms per liter (μg/L), with a median value of 24 μg/L (see Table 5; Appendix B). Similarly, dissolved copper concentrations range from 3.1 to 18 μg/L with a median value of 5.2 μg/L. For reported data that included both total and dissolved concentrations, 29 percent of the total copper was in the dissolved form. To provide a frame of reference for interpreting these results, the acute and chronic water quality standards for dissolved copper in surface waters of Washington state are 4.6 and 3.5 μg/L, respectively, based on a water hardness of 25 mg/L as $CaCO_3$. (This hardness concentration was derived based on a query of the Washington State Department of Ecology's Environmental Information Management database and represents the median value from 8,139 measurements that were made in water bodies throughout western Washington [EnviroVision and Herrera 2006]) Thus, the median dissolved copper concentration at edge of pavement exceeds the acute and chronic criteria. Considering the mean values from individual monitoring locations identified in Appendix B, the acute criterion was exceeded at 67 percent of the locations and the chronic criterion was exceeded at 86 percent of the locations.

However, it should be emphasized that the comparisons to state water quality made here and in subsequent sections are based on highway runoff concentrations measured at edge of pavement. As noted previously, highway runoff typically receives some treatment via natural process and/or engineered systems prior to the point of discharge to a receiving water. Furthermore, some dilution of the highway runoff will also occur at the point of discharge to the receiving water. Therefore, these comparisons are made for informational purposes only and should not be construed to represent actual violations of the applicable water quality standards within the receiving water.

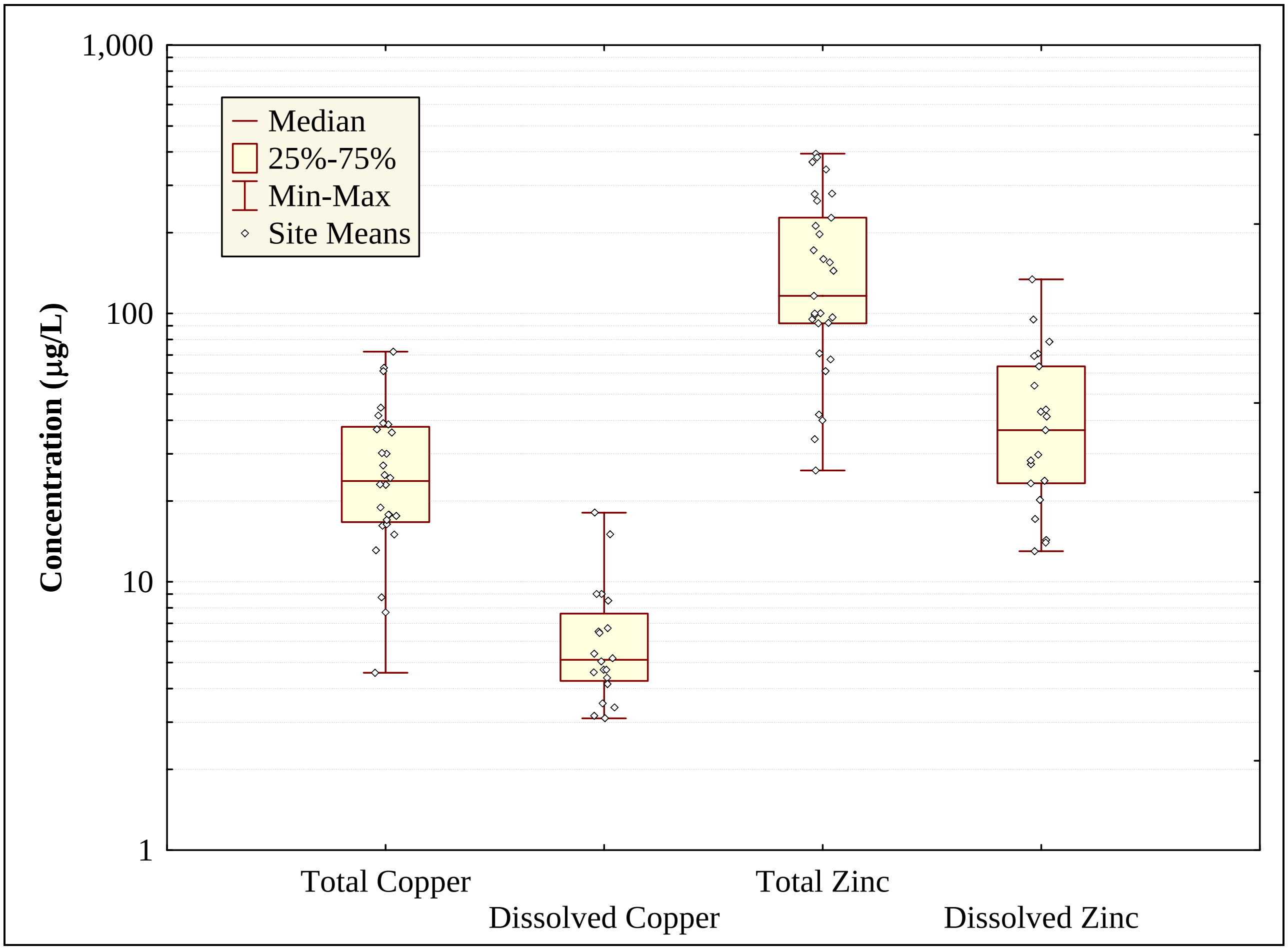

Figure 3. Mean concentrations of total and dissolved copper and zinc for western Washington sites.

Mean concentrations of total zinc from monitoring locations in western Washington range from 26 to 394 µg/L, with a median value of 116 µg/L (see Table 5; Appendix B). Dissolved zinc concentrations range from 13 to 134 µg/L with a median value of 39 µg/L. For comparison, the acute and chronic water quality standards for dissolved zinc are 35 and 32 µg/L, respectively, based on a median hardness concentration of 25 mg/L as $CaCO_3$ for receiving waters in western Washington (EnviroVision and Herrera 2006). Considering the mean values from individual monitoring locations identified in Appendix B, the acute and chronic criteria were both exceeded at 55 percent of the locations. Where the reported data included both total and dissolved concentrations, 31 percent of the total zinc was in the dissolved form.

Mean concentrations of total lead from monitoring locations in western Washington were highly variable. For example, these concentrations range from 24 to 1,065 µg/L with a median value of 120 µg/L (see Table 5; Appendix B). Dissolved lead concentrations were substantially lower, with a range from 1.0 to 3.2 µg/L and a median value of 2.1 µg/L. For comparison, the acute and chronic water quality standards for dissolved lead are 14 and 0.5 µg/L, respectively, based on a water hardness of 25 mg/L as $CaCO_3$. Thus, all dissolved lead concentrations exceed the chronic standard, but none exceed the acute standard. Where the reported data included both total and dissolved concentrations, 11 percent of the total lead was in the dissolved form.

It should be noted that the majority of the lead data used in this characterization are from older studies when leaded gasoline was prevalent and likely increased lead concentrations in runoff. However, lead can be deposited on highway surfaces from other sources such as vehicle tires, paints used on rights-of-way, and atmospheric deposition near industrial areas (Barber et al. 2006). Excluding lead data collected prior to 1990, total lead concentrations range from 24 to 61 μg/L with a median value of 27 μg/L. Dissolved lead was only measured at one location (i.e., Vancouver, WA) after 1990 where the mean concentration was 3.2 μg/L. For comparison, the acute and chronic water quality standards for dissolved lead are 14 and 0.54 μg/L, respectively, based on a median hardness concentration of 25 mg/L as $CaCO_3$ for receiving waters in western Washington (EnviroVision and Herrera 2006).

Concentrations of total arsenic, chromium, cadmium, and nickel in western Washington are lower than those reported in the national data (Table 5). However, these metals were measured at only one or two locations in Washington. Concentrations of these metals cannot be compared to applicable state water quality criteria because no data are available on their associated dissolved fractions.

Mean concentrations for antimony (4.9 μg/L), barium (82.4 μg/L), cobalt (3.2 μg/L), molybdenum (5.5 μg/L), and vanadium (10.5 μg/L) are available from only two Washington studies and there is no national data available for comparison (Table 5). There are no water quality criteria established for these metals. Total mercury data is only available from one location in western Washington (i.e., 520 Bridge) where a mean value of 0.02 μg/L was recorded. This value is lower than the acute criterion (2.1 μg/L) for mercury but higher than the chronic criterion (0.012 μg/L).

Based on the information presented in the preceding subsection, highest concentrations of total metals are expected during high intensity rain storms that influence transport-driven flushing behavior. Because dissolved metals are more influenced by flow-driven flushing behavior, highest concentrations of dissolved metals can be expected during the initial stages of a storm. However, as noted above, there are numerous other factors that may influence the magnitude of flushing behavior both before the storm (e.g., vehicle air turbulence) and during the storm (e.g., VDS). Therefore, generalizations about concentrations of metals in response to flushing behavior should be made with caution.

Finally, it should be noted that samples collected prior to the mid 1990s were prone to contamination by the standard sample and analysis practices employed at the time. Consequently, older monitoring results may have artificially elevated concentrations of some metals (Barber et al. 2006). More recent “clean” sample handing procedures and analysis techniques have improved the validity of data that are being collected for trace metal concentrations. As noted above, the majority of the data referenced in this report were collected after 1990 when these improved sampling procedures were in widespread use. Nonetheless, some caution should be exercised when interpreting metals data presented herein that were collected prior to the mid 1990s.

Nutrients

Sources of Nutrients in Highway Runoff

Nutrients in runoff are present in many forms. Nitrogen is typically measured as ammonia nitrogen, nitrate nitrogen, nitrite nitrogen, total Kjeldahl nitrogen (which is the sum of organic nitrogen and ammonia), and total nitrogen. Phosphorus is typically measured as orthophosphate phosphorus (also reported as soluble reactive phosphorus [SRP]) and total phosphorus. Ammonia, nitrate, nitrite, and orthophosphate are dissolved forms of nutrients.

In general, nutrients in highway runoff are a concern because they can stimulate excessive plant and algae growth in receiving waters. With the subsequent death and decomposition of this material, dissolved oxygen concentrations in the receiving water may become depleted. This process is referred to as eutrophication and has been observed throughout the United States (Beman et al. 2005; Breitburg 1990; Lehman et al. 2004; Rabalais et al. 2001). For example, lower Hood Canal in Washington is experiencing low oxygen conditions due to eutrophication, resulting in adverse effects on aquatic life (Mapes 2007). Ammonia and nitrite nitrogen can also be directly toxic to fish.

Based on data from both local and national studies, the main sources of nutrients in highway runoff are atmospheric deposition, vehicle exhaust (nitrogen oxides), and fertilizer applications (as nitrogen and phosphorus) on rights-of-way (Irish et al. 1998; Yonge et al. 2002). In addition, one local study of highway runoff (King County 2006) also showed that bird droppings can be a significant source of nutrients.

Factors Affecting Nutrients in Highway Runoff

Unlike metals, nutrients are often found in dissolved form. Based on data from national studies, only total phosphorus shows a consistent relationship with suspended solids (Barrett et al. 1995a; Kearfott et al. 2005). However, Chui (1981) found a correlation between TSS and nutrients in western Washington.

Other national studies on factors affecting nutrients in highway runoff have found no correlation between ADT and nutrients (Barrett et al. 1995a; Kayhanian et al. 2003). More reliable predictors of nutrients in highway runoff from national studies are the number of vehicles during storms (Kerri et al. 1985) and other dry period conditions (Irish et al. 1998). For example, Irish et al. (1998) showed that nitrate and total phosphorus concentrations were influenced by ADT between storms and antecedent dry periods. However, because the primary sources of nutrients are atmospheric deposition and agricultural fertilizer applications, land use is likely the most important factor influencing the concentrations of nutrients in highway runoff (Driscoll et al. 1990; Gupta et al. 1981).

Some forms of nitrogen and phosphorus also display first flush characteristics. For example, a study by Yonge et al. (2002) in western Washington indicated that ammonia, total Kjeldahl nitrogen, and total phosphorus show strong first flush characteristics, but nitrate and orthophosphate phosphorus do not.

Concentrations of Nutrients in Highway Runoff

Most forms of nitrogen and phosphorus have been reported in western Washington highway runoff (Figure 4). Ammonia nitrogen was reported for only two studies, with a mean concentration of 1.84 mg/L. This concentration is higher than the range reported in the national data (0.07 to 0.22 mg/L, Table 5).

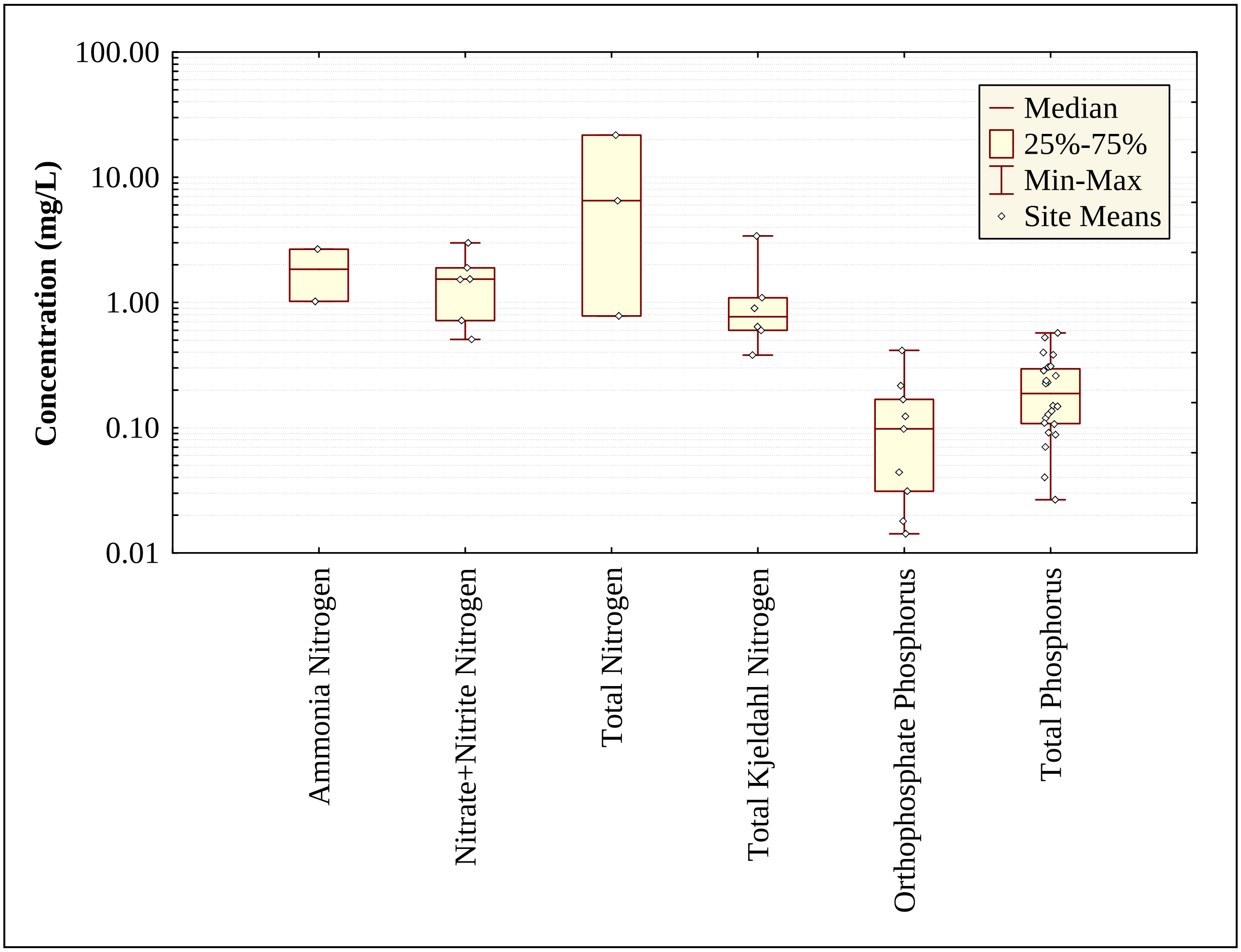

Figure 4. Mean concentrations of nutrients in western Washington highway runoff.

The concentration of nitrite nitrogen is usually very low in aquatic systems because nitrite converts to nitrate very rapidly in the presence of oxygen; therefore, the combination of nitrate+nitrite nitrogen is more commonly reported than individual measures of nitrate and nitrite. Mean concentrations of nitrite+nitrate nitrogen in western Washington range from

0.47 to 2.99 mg/L, which is similar to the range of mean concentrations reported in the national data (0.15 to 1.64 mg/L, Table 5). The median value for nitrite+nitrate nitrogen in western Washington is 1.54 mg/L (see Appendix B).

Mean concentrations of total Kjeldahl nitrogen in western Washington range from 0.38 to 3.4 mg/L, which is within the range in the national dataset (0.34 to 55.0 mg/L, Table 5). The median value for total Kjeldahl nitrogen in western Washington is 0.77 mg/L (see Appendix B).

As shown in Figure 4, mean concentrations of total nitrogen in highway runoff exhibit a wide range across the three monitoring locations where this parameter was measured in western Washington. The mean concentrations of total nitrogen from these locations range from 0.78 to 21.7 mg/L while the median value from these locations is 6.5 mg/L (see Table 5; Appendix B). These values are generally similar to the value reported in the national dataset of (4.1 mg/L, Table 5).

Concentrations of orthophosphate phosphorus in western Washington range from 0.01 to 0.42 mg/L (Table 5). Concentrations of total phosphorus in western Washington range from 0.03 to 0.57 mg/L (Table 5). Total phosphorus is the best represented nutrient parameter in the region, with data from more than 20 sites. This range is lower than the range in the national dataset (0.113 to 0.998 mg/L, Table 5).

Organic Compounds

Sources of Organic Compounds in Highway Runoff

Pollutants in this category include several common measures of contamination from vehicle fuels and emissions such as oil and grease, total petroleum hydrocarbons (TPH), and polycyclic aromatic hydrocarbons (PAHs). TPH is often separated into the heavy fraction (TPH-oil) and the lighter diesel fraction (TPH-diesel). Sources of PAHs include asphalt sealant leaching, vehicle emissions, lubricating oils, tire abrasion, and atmospheric deposition (Ngabe et al. 2000; Lopes and Dionne 1998; Yonge et al. 2002). The predominant source of PAHs has been reported to be vehicle emissions in some studies (Ngabe et al. 2000; Lopes and Dionne 1998; Yonge et al. 2002); other studies indicate that atmospheric deposition is the predominant source (Hoffman et al. 1984). Evidence of emissions as the source of PAHs is provided by studies indicating that PAHs in soils decrease with increasing distance from highways (Lopes and Dionne 1998; Hewitt and Rashed 1990). The primary source of oil and grease and TPH is vehicles (Barrett et al. 1995a).

Highway runoff may also contain other organic compounds that are not directly related to vehicles such as herbicides, pesticides, and polychlorinated biphenyls (PCBs). These pollutants are commonly persistent in nature; they can bioaccumulate in fish (Yonge et al. 2002). Sources of organic pollutants are atmospheric deposition (PCBs) and application of herbicides and pesticides on highway rights-of-way (Barrett et al. 1995a).

Factors Affecting Organic Compounds in Highway Runoff

One of the most significant factors affecting PAH concentrations in highway runoff is sediment (Lopes and Dionne 1988; Irish et al. 1998). PAHs have a low solubility in water; therefore, they often bind to particles and tend to accumulate in the upper layer of soil (Yonge et al. 2002). National studies have shown that 70 to 99 percent of PAHs were removed from the road surfaces by winds, similar to the effect of wind on TSS concentrations (Hewitt and Rashed 1990). Furthermore, Barrett et al. (1995a) point out that PAHs concentrations on roads can be reduced by volatilization, photo-oxidation, and other oxidation processes. Locally, Zawlocki (1981) showed a strong correlation between PAHs and TSS in Seattle highway runoff. This study also showed that land use influenced PAH concentrations, with higher amounts in highway runoff, snowmelt, and industrial areas compared to commercial and residential areas (Hoffman et al. 1984; Hoffman et al. 1985).

A survey of national studies shows a strong correlation between oil and grease and ADT (Irish et al. 1998; Kayhanian et al. 2003). In addition, the concentration of oil and grease depends on factors such as runoff volume, number of vehicles during storms (Irish et al. 1998), antecedent dry period, and total rainfall (Khan et al. 2006). The concentration of oil and grease is not greatly affected by the type of highway surface. However, the concentration has been observed to be higher in runoff from concrete compared to asphalt (Barrett et al. 1995a), although this is not a dominant factor. Oil and grease and TPH also show first flush behavior (Hoffman et al. 1985; Khan et al. 2006; TRB 2006). However, the first flush behavior is more pronounced during snowmelt than rain runoff (TRB 2006).

In contrast to these national studies, a study in Seattle that evaluated trace organic compounds (Table 6) in highway runoff showed no correlation between the concentrations and the amount of rainfall, traffic volume, or runoff volume (Zawlocki 1981). However, the study did show that the concentrations of organic compounds in Seattle vicinity highway runoff were greatly affected by TSS concentrations. In general, local studies on factors affecting organic compounds are lacking.

Concentrations of Organic Compounds in Highway Runoff

Although petroleum hydrocarbons are prevalent in highway runoff and can be toxic, few studies have measured the concentrations of these organic compounds in western Washington. Data for Washington were obtained from a study of trace organic compounds in Seattle (Zawlocki 1981, Table 6), a highway runoff study near Woodinville (St. John and Horner 1997), a survey of PAHs in runoff in Spokane and Vancouver, Washington (Yonge et al. 2002, Table 7), a survey of organics from a study of bridge runoff from SR 520 (King County 2006), and a compilation of oil and grease and TPH data collected to evaluate WSDOT best management practices for highway runoff (Figure 5). All of these studies were conducted in urban areas; hence, data for more rural highways are currently not available. Data from these studies are summarized in Appendix B and in Tables 6-8.

Table 6. Extractable organic compounds in Seattle highway runoff classified into nine categories.

Class of Compounds	Sample Storm I-5-87			Sample Storm I-5-131			Sample Storm 520-43		
	Particulate (µg/L)	Soluble (µg/L)	Total (µg/L)	Particulate (µg/L)	Soluble (µg/L)	Total (µg/L)	Particulate (µg/L)	Soluble (µg/L)	Total (µg/L)
Alcohols	T	160	160	478	155	633	327	126	453
Aliphatic hydrocarbons	3,710	3,220	6,930	1,850	636	2,490	913	20	933
Aromatic compounds, including heterocyclic compounds	2,050	148	2,200	297	96	393	596	128	724
Halogenated organic compounds	T	T	T	175	9	82	114	T	114
Ketones and aldehydes	1,130	T	1,130	87	39	126	385	128	513
Organosulfur compounds	1,200	62	1,260	T	5.3	5.3	4.9	T	4.9
Oxygenates, excluding alcohols, phenolic compounds, ketones, and aldehydes	3,170	410	3,580	3,510	228	3,740	2,440	126	2,570
Nitrogen-containing compounds	1,420	62	1,480	87	28	115	325	135	460
Phenolic compounds	2,830	80	2,910	T	2.9	2.9	T	T	T
Total analyzed by chromatography	10,236	6,803	17,039	6,308	1,204	7,512	4,083	320	4,403

Source: Zawlocki (1981).
I-5 – Interstate 5.
520 – State Route 520.
µg/L = micrograms per liter.
T = trace.

Table 7. Polycyclic aromatic hydrocarbon concentrations (µg/L) in 19 samples of highway runoff collected in Spokane and Vancouver, Washington, and ranked in decreasing order of detection frequency.

Sample ID	SICOM1	SICOM2	SICOM3	SICOM1	SICOM3	SICOM2	VICOM	VICOM	VICOM	VICOM	VICOM	VICOM1	SICOM1	SICOM2	VICOM	SICOM2	SICOM3	VICOM2	SICOM1	No. of samples > MDL
Sampling Date	2/18/1999	2/18/1999	2/18/1999	9/9/1998	9/9/1998	9/9/1998	11/19/1998	1/17/1999	4/21/1999	6/15/1998	6/15/1998	3/29/1999	12/17/1997	12/17/1997	5/17/1998	9/16/1998	9/16/1998	3/29/1999	9/16/1998	
Pyrene	2.3	2.4	2.2	0.68	0.29	0.56	0.76	0.51	0.57	0.14	0.14	0.21	0.49	0.42	0.16	0.26	.22.	0.23	ND	18
Phenanthrene	1.1	1.2	1.1	0.56	0.18	0.43	0.37	0.17	0.23	0.14	0.14	ND	0.19	0.15	ND	0.39	0.23	ND	0.13	16
Fluoranthene	1	1.3	1.2	0.48	0.24	0.39	0.66	0.37	0.54	0.13	0.13	0.19	ND	ND	0.16	0.29	0.16	0.2	ND	16
Chrysene	2.5	2.7	2.3	0.92	0.52	0.58	0.42	0.21	0.48	0.11	0.11	ND	0.47	ND	0.12	ND	ND	ND	ND	13
Benzo(a)anthracene	0.54	0.52	0.53	ND	ND	ND	0.29	0.16	0.22	ND	ND	0.15	ND	ND	ND	ND	ND	0.16	ND	8
Naphthalene	0.12	0.18	0.18	0.75	0.86	0.73	0.45	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	7
2-Methylnaphthalene	0.13	0.18	0.17	0.95	1	0.94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	6
Benzo(b)fluoranthene	0.58	0.56	0.42	ND	ND	ND	ND	0.16	ND	ND	ND	ND	ND	0.12	ND	ND	ND	ND	ND	5
Anthracene	0.11	0.13	0.13	ND	0.19	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	4
Fluorene	0.13	0.18	0.18	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3
Benzo(k)fluoranthene	0.13	0.22	0.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3
Benzo(a)pyrene	0.92	1	0.95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3
Benzo(g,h,i)perylene	ND	ND	ND	0.33	ND	ND	ND	ND	ND	ND	ND	0.2	ND	ND	ND	ND	ND	ND	ND	2
2-Chloronapthalene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0
Acenapthylene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0
Acenapthene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0
Indeno(1,2,3-cd)pyrene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0
Dibenz(a,h)anthracene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0
No. of samples > MDL	12	12	12	7	7	6	6	6	5	4	4	4	3	3	3	3	3	3	1	

Source: Yonge et al. (2002).
MDL = method detection limit.
µg/L = micrograms per liter.
ND = not detected.
S = Spokane, Washington.
V = Vancouver, Washington.

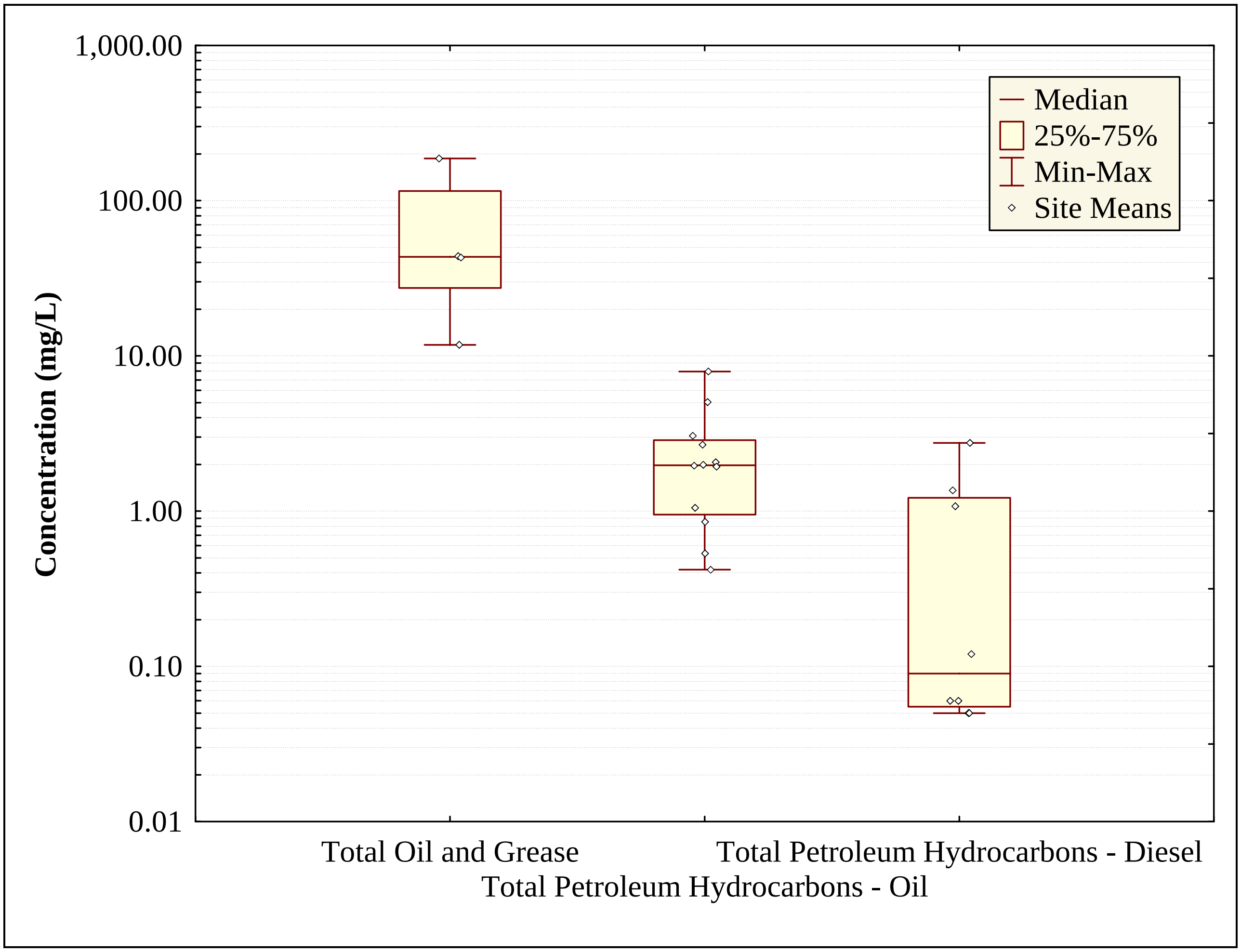

Figure 5. Mean concentrations of petroleum compounds for western Washington highway runoff.

Organic compounds were identified and measured for dissolved and particulate fractions in three samples in highway runoff in the Seattle vicinity (Zawlocki 1981). Concentrations of these organic compounds are summed by functional group in Table 6. These results are presented by functional group because many compounds could not be completely identified at the time of the study. Concentrations of all of the identified organic compounds were less than water quality criteria for the protection of aquatic life in Washington that were in effect at the time of the study (Zawlocki 1981).

Inflow of highway runoff into two wet ponds was analyzed for 18 PAHs in 19 samples (Yonge et al. 2002). The results are ranked in decreasing order of detection frequency in Table 7. The five most commonly detected PAHs over multiple storms were pyrene, fluoranthene, phenanthrene, chrysene, and benzo(a)anthracene. These PAHs, which are byproducts of the incomplete combustion of fuels, are components of vehicle emissions (Yonge et al. 2002). Other PAHs that were analyzed in connection with this study were detected during some storms but not others, or never detected during any storm at either of the two monitoring locations (Table 7).

Table 8. Concentrations of organic compunds from SR 520 bridge runoff.

Parameter	Average of All Storms	Median of All Storms	Range
Petroleum Hydrocarbons			
Lube Oil Range (>C24)	4.4	2.6	1.4-11
LPAHs			
2-Methylnaphthalene	0.06	0.05	0.05-0.10
Naphthalene (µg/l)	0.06	0.06	0.02-0.1
Phenanthrene (µg/l)	0.17	0.13	0.02-0.42
HPAHs			
Benzo(a)anthracene (µg/l)	0.12	0.17	0.01-0.19
Benzo(a)pyrene (µg/l)	0.16	0.19	0.05-0.24
Benzo(b)fluoranthene (µg/l)	0.13	0.05	0.05-0.22
Benzo(k)fluoranthene (µg/l)	0.08	0.05	0.05-0.23
Benzo(g,h,i)perylene (µg/l)	0.16	0.08	0.05-0.39
Chrysene (µg/l)	0.18	0.16	0.02-0.39
Fluoranthene (µg/l)	0.27	0.17	0.05-0.65
Indeno(1,2,3-cd)pyrene (µg/l)	0.15	0.20	0.05-0.27
Pyrene (µg/l)	0.35	0.25	0.02-0.86
Phthalates			
Benzyl butyl phthalate (µg/l)	0.53	0.48	0.48-0.71
Di-n-butyl phthalate (µg/l)	0.58	0.51	0.48-0.90
Di-n-octyl phthalate (µg/l)	1.9	2.1	0.48-3.4
Ionizable organic compounds			
2,4-Dimethylphenol (µg/l)	0.25	0.21	0.05-0.54
2-Methylphenol (µg/l)	0.59	0.49	0.35-1.1
Benzoic acid (µg/l)	1.8	1.7	0.77-3.6
Benzyl alcohol (µg/l)	0.59	0.51	0.10-1.8
2,4-Dinitrophenol (µg/l)	0.69	0.48	0.47-1.2
4,6-Dinitro-o-cresol (µg/l)	0.35	0.47	0.05-0.48
3-Methylphenol (µg/l)	0.39	0.55	0.5-0.57
4-Nitrophenol (µg/l)	2.0	1.4	0.47-5.1
Miscellaneous Extractables			
Bis(2-ethylhexyl)adipate (µg/l)	0.78	0.60	0.24-2.1
Bisphenol A (µg/l)	3.8	3.3	1.6-7.3
Caffeine (µg/l)	1.3	0.86	0.38-5.1
Carbozole (µg/l)	0.04	0.02	0.02-1.0
Total 4-Nonylphenol (µg/l)	3.5	2.6	0.48-9.1

Source: King County (2006)
PAH – polycyclic aromatic hydrocarbons.
µg/l – micrograms per liter.

King County (2006) conducted a study of highway runoff from the Evergreen Point Floating Bridge (SR 520 Bridge) that included the characterization of several organic compounds

(Table 8). A total of 31 organic compounds were detected in highway runoff from this sampling. These results showed that bis(2-ethylhexyl)phthalate was present in the highest concentrations. This pollutant was also measured in highway runoff at a monitoring location near Woodinville, Washington (St. John and Horner 1997). In general, this pollutant belongs to a class of compounds called phthalates that are present in many consumer products including plastics (King County 2006). The King County study also found high concentrations of bisphenol A and 4-nonylphenol in the highway runoff from the SR 520 Bridge. Bisphenol A is a plasticizer used in a wide variety of consumer products and 4-nonylphenol is used as a surfactant in products such as pesticides and detergent gasoline and oils (King County 2006). Concentrations of all the detected compounds in this study were below U.S. EPA (2006) recommend criteria for the protection of aquatic life and human health.

Mean concentrations of oil and grease from monitoring locations in western Washington range from 11.8 to 187.0 mg/L, while the median value from these locations is 43.5 mg/L. Samples for analysis of oil and grease were collected at only three sites, but this parameter was detected in all of the collected samples.

Concentrations of TPH-oil range from 0.42 to 7.94 mg/L and have a median value of 1.97 mg/L. In comparison, concentrations of TPH-diesel were lower with a range of 0.05 to 2.75 mg/L and median value of 0.09 mg/L. TPH-oil was detected in all of the samples, but TPH-diesel was detected in only 40 percent of the samples.

Few data on PCBs in highway runoff are currently available for western Washington. However, in a study of trace organic compounds in Seattle, Washington detected no PCBs in highway runoff during the 1977–1981 study period (Zawlocki 1981). Beginning in the 1970s, PCBs were banned for all uses in the United States. Although these compounds are highly persistent within the environment, they are not expected to be a major contaminant of concern in highway runoff.

There are also few data on pesticide and herbicide concentrations in highway runoff for western Washington. Table 9 lists deicers and herbicides that are currently being used in conjunction with WSDOT's road maintenance operations and represent chemicals that could be present in highway runoff. National data are also very limited for herbicides and pesticides in highway runoff. However, a few studies of herbicide runoff in California have shown that herbicides applied to right-of-ways were detected in runoff in varying amounts. Huang et al. (2004) measured event mean concentrations (EMCs) for oryzalin, isoxaben, diuron, clopyralid, and glyphosate. Their results showed that over 11 different storms, herbicide EMCs ranged from not detected to 43 µg/L for oryzalin. Glyphosate is the only herbicide studied by Huang et al. (2004) and used by WSDOT (see Table 9). Glyphosate concentrations reported by Huang et al. (2004) ranged from 1.4 to 9.4 µg/L. However, it is unclear if these results are representative of conditions in western Washington. In general, WSDOT has developed an integrated vegetation management (IVM) program which controls undesirable roadside vegetation while establishing stable low maintenance plant communities. This program uses a variety of maintenance activities to control roadside vegetation issues including native vegetation plantings, mechanical mowing, hand removal and targeted chemical applications. As a result, herbicide applications have been dramatically reduced over levels observed prior to 2005.

Table 9. Chemicals used by WSDOT for highway maintenance activities (Anderson 2007).

Maintenance Activity	Chemical Name(s)
Deicing	Calcium Chloride Calcium Magnesium Acetate Sodium Chloride
Vegetation management (herbicides)	Telar™ (Chlorsulfuron) Oust™ (Sulfometuron methyl) Crossbow™ (Metsulfuron methyl) Krenite S™ (ammounium salt of fosamine) Roundup™ (isopropylamine salt of glyphosate) Landmark™ (Sulfometuron methyl and Chlorsulfuron) Garlon 4™ (Triclopyr butoxyethyl ester and kerosene Rodeo™ (isopropylamine salt of glyphosate)[a]

[a] Rodeo is the same chemical as Roundup but without surfactants included.

As noted above, many organic pollutants are hydrophobic and tend to be associated with sediments (Yonge et al. 2002). Therefore, maximum concentrations for these pollutants can be expected during high intensity storms that tend to mobilize these sediments; whereas less intense storms of longer duration will generally reduce pollutant concentrations (EWGCC 2000).

Bacteria

Sources of Bacteria in Highway Runoff

Bacteriological contamination of highway runoff is most commonly assessed using measurements of total and fecal coliform bacteria. The presence of these bacteria is not necessarily a direct threat to public health. However, their use as an indicator of potential fecal contamination is considered important for the early detection of potential health threats. The major source of these bacteria in highway runoff is the incidental presence of animals on the pavement surface and adjacent embankments (Kearfott et al. 2005). In a recent study by King County, bacteria in runoff from the SR 520 Bridge was attributed to bird droppings.

Factors Affecting Bacteria in Highway Runoff

There have not been many detailed studies on factors that affect the concentrations of bacteria in highway runoff; therefore, the available information is limited. However, like many pollutants in highway runoff, bacteria are often associated with particles and sediments (EWGCC 2000). Therefore, factors influencing TSS should also affect bacteria. For example, intense storms that result in the movement of a large quantity of sediment increase the potential for bacteria in runoff (Kearfott et al. 2005). As side from the study referenced above from the SR 520 Bridge, factors affecting bacteria concentrations in highway runoff have not been thoroughly investigated within western Washington.

Concentrations of Bacteria in Highway Runoff

Concentrations of total coliform bacteria in highway runoff in western Washington have been measured in only one study (Sylvester and DeWalle 1972); the mean concentration was 9,350 colony-forming units (CFU) per 100 milliliters (mL) (Figure 6). This concentration is higher then the range reported in the national dataset (570 to 6,200 CFU per 100 mL, Table 5).

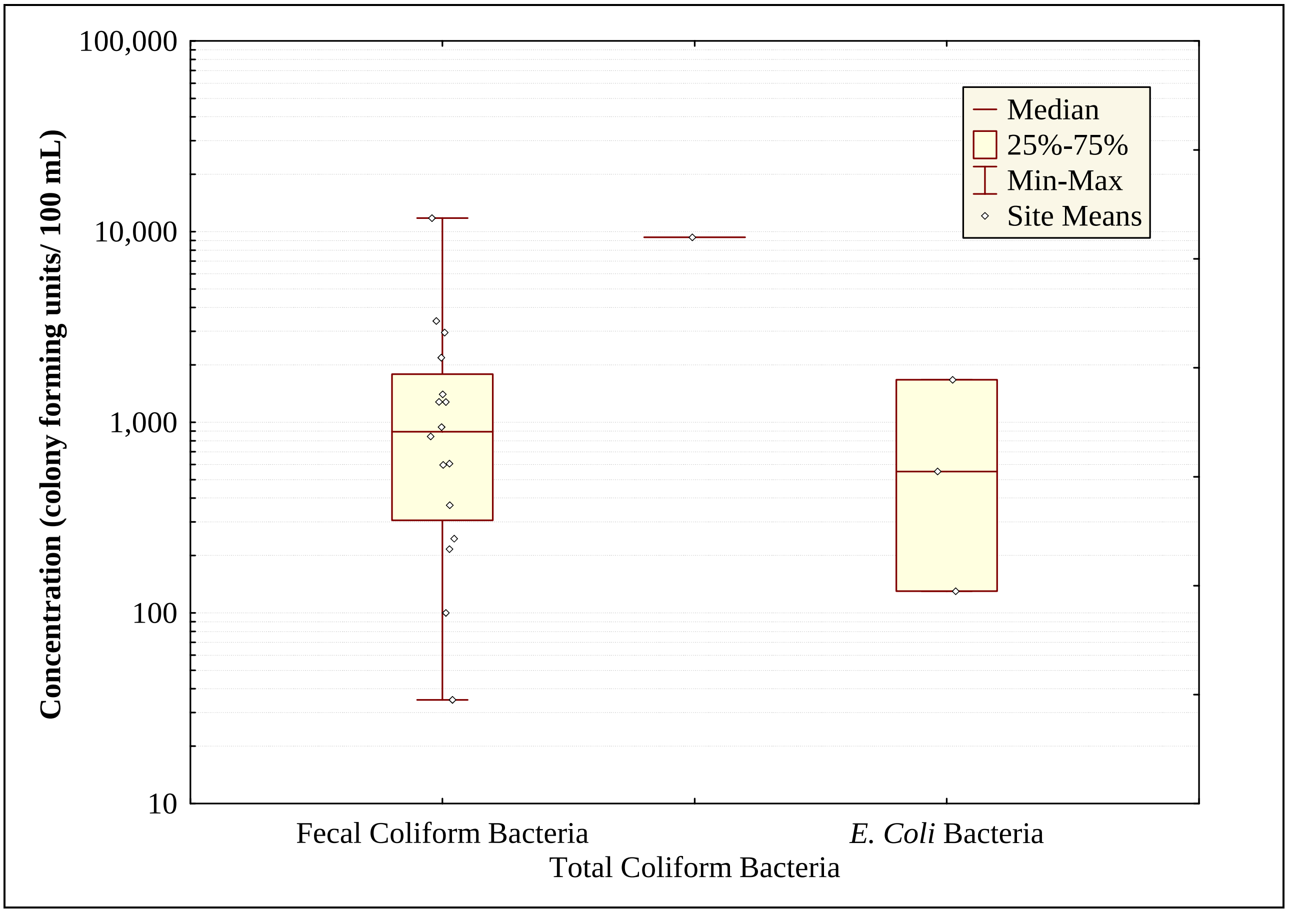

Figure 6. Mean concentrations of total and fecal coliform bacteria for highway runoff sites in western Washington.

Data for fecal coliform bacteria are available from 16 monitoring locations in western Washington and include recently collected data from King County (2006), WSDOT (2006), and Herrera (2007). Mean concentrations from these monitoring locations range from 35 to 11,775 CFU per 100 mL, while the median value from these is 892 CFU per 100 mL. This median value exceeds the range reported for the national dataset (50 to 590 CFU per 100 mL, Table 5). *E. coli* was measured at three locations in western Washington (King County 2006) with a range of 130 to 1,670 CFU per 100 mL and a median value of 551 CFU per 100 mL. As noted above, maximum concentrations of both total and fecal coliform bacteria will likely be associated with intense storms that mobilize significant quantities of sediment in combination with areas where animals are typically present.

Oxygen Demand

Sources of Oxygen Demand in Highway Runoff

Two parameters often measured in highway runoff are chemical oxygen demand and biological oxygen demand. Chemical oxygen demand is a measure of the total oxygen required to oxidize all compounds, both organic and inorganic, in water. Chemical oxygen demand is expressed in milligrams per liter, which indicates the amount of oxygen consumed per liter of solution. Biological oxygen demand is a test used to measure the concentration of biodegradable organic matter in runoff. Biological oxygen demand is typically measured over a period of 5 days, and the results are referred to as the 5-day biological oxygen demand (BOD_5).

Factors Affecting Oxygen Demand in Highway Runoff

National studies (Irish et al. 1998) have shown that chemical oxygen demand correlates with TSS and oil and grease (Khan et al. 2006). In western Washington, Chui (1981) also showed that chemical oxygen demand correlates with TSS. Biological oxygen demand correlates with ADT during both dry and wet periods (Irish et al. 1998). Furthermore, Kerri et al. (1985) showed that the number of vehicles during storms correlated more strongly with chemical oxygen demand than other traffic measures.

Concentrations of Oxygen Demand in Highway Runoff

Chemical oxygen demand is, on average, higher than biological oxygen demand because COD oxidizes inorganic and organic compounds that do not degrade by microorganisms within 5 days. Mean chemical oxygen demand concentrations at monitoring locations in western Washington range from 32 to 1,377 mg/L, and the median value from this data is 106 mg/L (Figure 7). For comparison, chemical oxygen demand concentrations exhibit a lower range (from 14.7 to 272 mg/L) in the national dataset (Table 5). Mean biological oxygen demand concentrations at monitoring locations in western Washington range from 9.5 to 71 mg/L, and the median value from this data is 40.3 mg/L. This median value exceeds the range from the national dataset (12.7 to 37 mg/L, Table 5). However, it should be noted that recent data on oxygen demand in highway runoff are lacking for western Washington.

Conventional Water Quality Parameters

Several conventional water quality parameters are typically measured in highway runoff to serve as general measures of water quality or to facilitate interpretation of data for other parameters. Common conventional parameters include turbidity, hardness, alkalinity, pH, specific conductivity, and total organic carbon. Although these parameters are informative, they typically are not correlated with other factors influencing pollutant concentrations that were discussed throughout this report. One exception is turbidity, which is a measure of water clarity. Turbidity is expected to correlate with TSS and would be influenced by factors such as storm intensity.

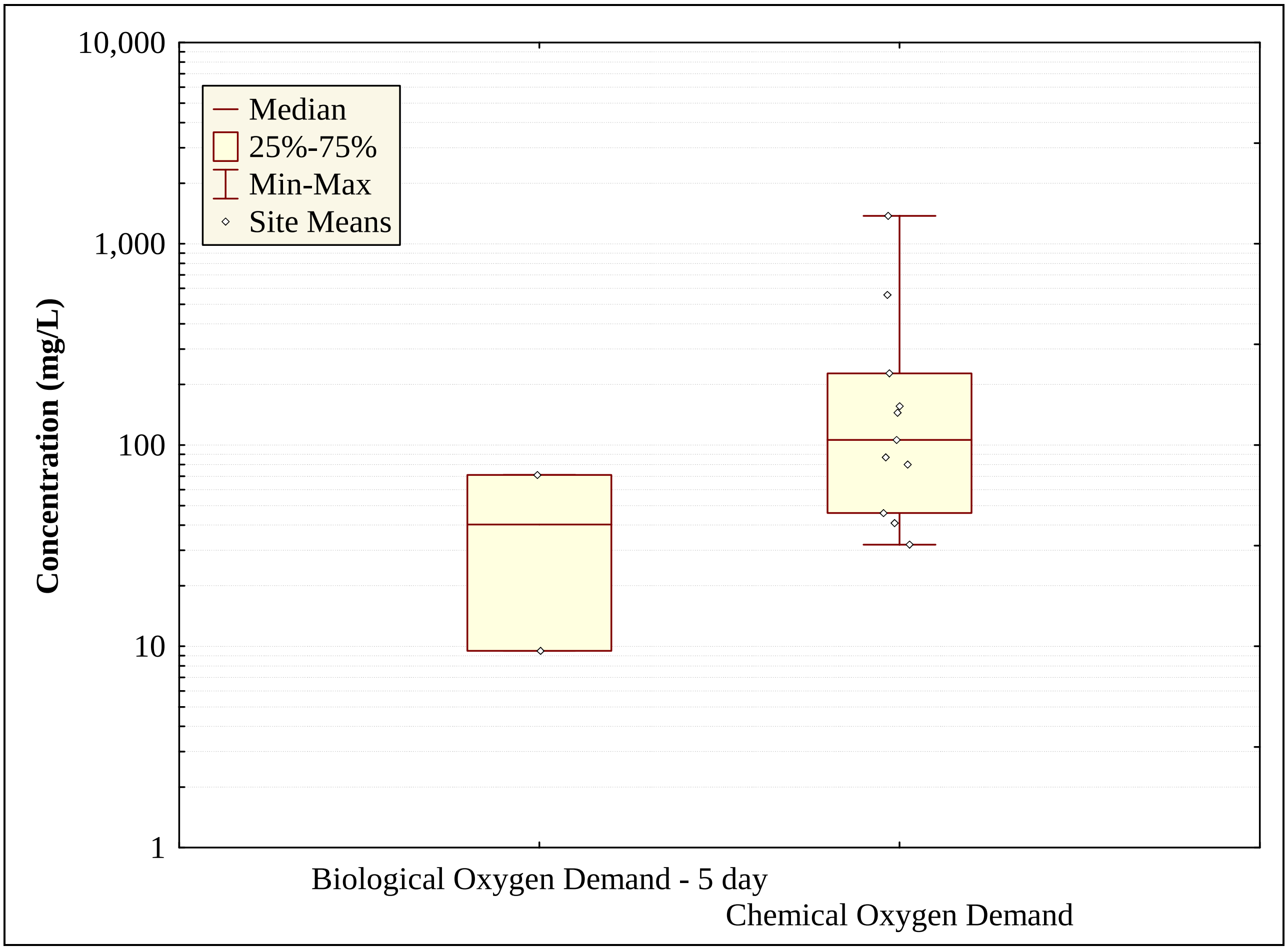

Figure 7. Mean concentrations of chemical oxygen demand and 5-day biological oxygen demand for highway runoff sites in western Washington.

In western Washington, hardness values range from 11.1 to 86.1 mg/L, and alkalinity ranges from 19.3 to 23.4 mg/L (Figure 8). The pH was measured at five sites in western Washington, resulting in ranges from 5.8 to 6.8, which is slightly lower than the range of 7.1 to 7.2 (Table 5) reported by Barrett et al. (1995a) from the national data. Conductivity was measured at only one site (St. John and Horner 1997), and the result was reported as 71.6 microsiemens (µS/cm), which is less than the range of values in the national data (337 to 500 µS/cm, Table 5). Finally, mean total organic carbon concentrations from monitoring locations in western Washington range from 2 to 139 mg/L, while the median value from these data is 21 mg/L. These values generally encompass the range reported for total organic carbon (24 to 77 mg/L) in the national data.

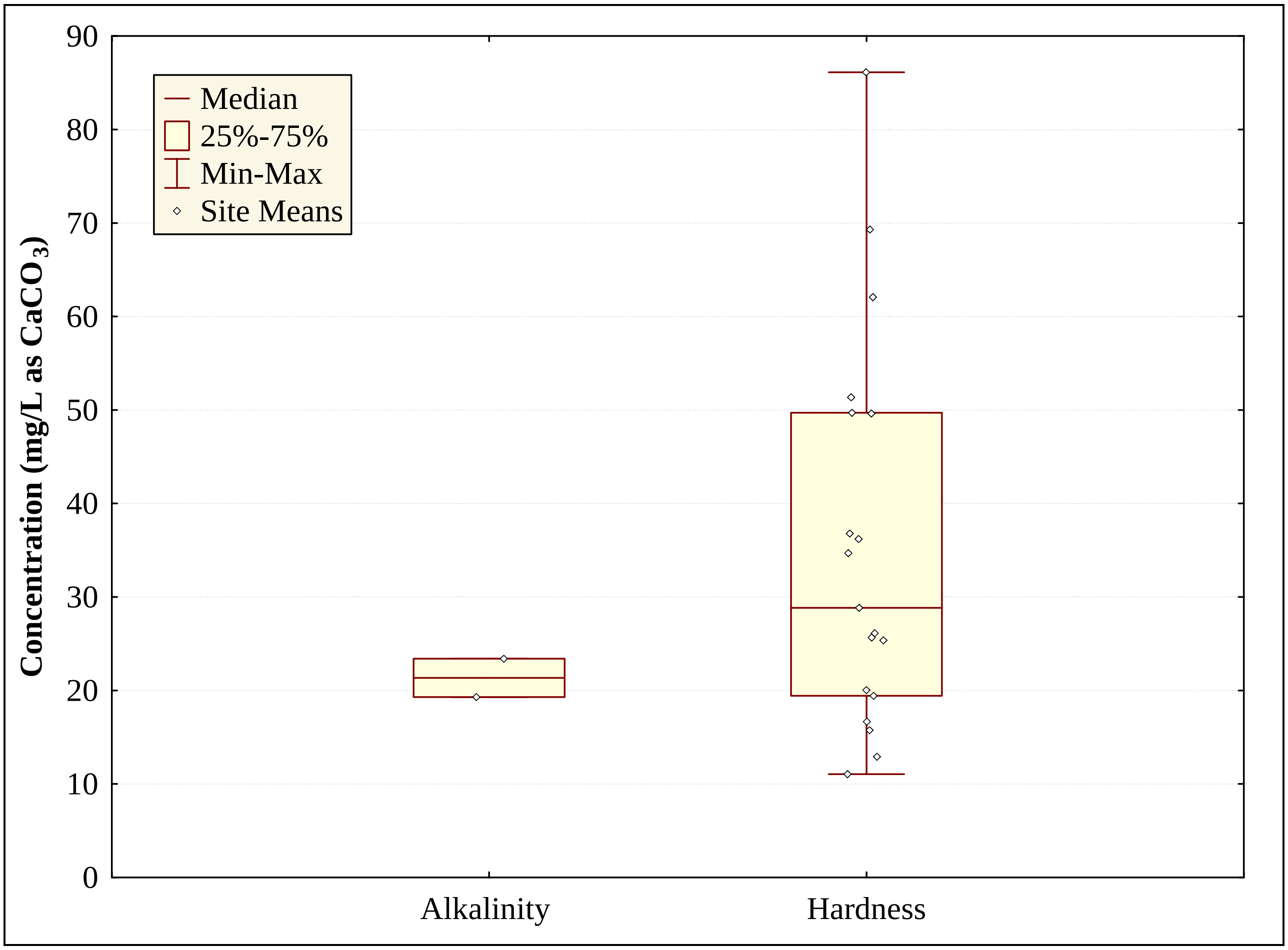

Figure 8. Mean values for conventional parameters measured in western Washington highway runoff.

Conclusions

This white paper identifies the major pollutants that are present in untreated highway runoff within western Washington, their associated sources, and potential factors that may influence their concentrations. To the extent possible, this information was derived from data that are specific to western Washington. This white paper will ultimately provide the foundation for two subsequent white papers that will document how untreated runoff is modified during the treatment process and the effects of runoff on ESA listed species. This white paper makes the following general conclusions for pollutants in highway runoff in western Washington:

Suspended Solids

- Suspended solids are a particular concern because they are typically associated (bound) with other pollutants including metals, organic compounds, nutrients, and bacteria.
- Rainfall intensity is an important influence on suspended solids concentrations with higher intensity events having more energy to mobilize this pollutant.
- National and local studies have shown that ADT is generally not a good predictor of suspended solids in highway runoff; rather, better predictors for this parameter include VDS and antecedent dry period. However, natural winds and vehicle-generated turbulence in the region can remove a large fraction of the suspended solids that have been deposited on highway surfaces. This, in turn, can reduce the strength of the correlation between suspended solids and antecedent dry period.
- In western Washington, land use has been reported to be one of the more important factors affecting suspended solids in highway runoff. In general, concentrations of suspended solids and associated pollutants tend to be higher near urban areas. National studies have also found higher amounts of atmospheric dust fall on highways near urban areas.
- Maximum conditions of suspended solids are likely to occur in conjunction with road sanding events, when TSS concentrations can reach well over 900 mg/L.

Metals

- Because of the strong correlation between suspended solids and metals, factors that effect suspended solids concentrations also apply to metals. These factors include rainfall intensity, VDS, and antecedent dry period.

However, similar to TSS, natural and vehicle generated winds in western Washington can remove a large fraction of the metals that have been deposited on highway surfaces, thereby reducing the strength of the correlation between metals and antecedent dry period.

- Metals also exhibit first flush characteristics that vary by metal species. More specifically, first flush behavior is more common for dissolved metals than particulate-bound metals.

- Local studies indicate rainfall patterns may control the extent of first flush behavior for various metals. For example, first flush behavior was shown to be less common in western Washington relative to eastern Washington due to the small, frequent rain events that are common in this marine-influenced region. Furthermore, the degree of first flush behavior in western Washington has been shown to increase after longer antecedent dry periods. However, both national and local studies have also shown that with increasing antecedent dry periods, other factors such as atmospheric deposition, air turbulence (due to wind and vehicles), and volatilization/oxidation can reduce the correlation between metal concentrations in runoff and the length of the antecedent dry period.

- Based on one study conducted in western Washington, the particulate-bound and dissolved fractions of the following metals showed a propensity for first flush behavior in order from greatest to least: lead, zinc, copper, and cadmium.

- Copper, zinc and manganese were shown to be the most bioavailable metals in one local study of highway runoff.

- Surrounding land use can influence concentrations of metals in highway runoff with proximity to industry resulting in higher metals concentrations due to atmospheric deposition.

- Monitoring data show that copper and zinc are very common in highway runoff. Lead is detected less frequently since the elimination of leaded gasoline. Concentrations of copper, zinc, and lead in highway runoff within western Washington are generally lower than the ranges reported from national studies. Based on the limited amount of available data, concentrations of other metals (e.g., arsenic, chromium, cadmium, and nickel) are also generally lower than those reported from the national data.

- Concentrations of dissolved copper and zinc measured at edge of pavement often exceed acute and chronic water quality standards based on a representative hardness concentration for receiving waters in western Washington. Furthermore, concentrations of dissolved lead often exceeded the chronic water quality standard based on this same hardness concentration. However, the concentrations reported herein for these metals are not considered representative of the pollutant concentrations at the point of discharge to receiving waters because highway runoff typically receives some treatment via natural and/or engineered systems after leaving the edge of pavement.

- Maximum concentrations for total metals can be expected to occur during high intensity rain storms that influence transport-driven flushing behavior. Because dissolved metals are more influenced by flow driven flushing behavior, maximum concentrations of dissolved metals are expected during the initial stages of a storm. However, the magnitude of the flushing behavior can be difficult to predict because it can be influenced by a number of other factors (e.g., VDS, antecedent dry period, etc.). Therefore, generalizations about maximum metals concentrations should be made with caution.

Nutrients

- In western Washington, nutrients have been shown to be correlated with TSS and will likely respond in a similar fashion in response to precipitation and other factors that influence pollutant concentrations in highway runoff.
- Because the primary sources of nutrients are atmospheric deposition and fertilizer applications, land use is likely one of the more important factors influencing their associated concentrations in highway runoff.
- Some national studies have shown that VDS, ADT between storms, and antecedent dry period can be reliable predictors of nutrient concentrations in highway runoff. However, given the region's unique precipitation patterns, the degree to which nutrient concentrations are similarly influenced by these factors in western Washington is unclear.
- Some forms of nitrogen and phosphorus have been shown to exhibit first flush characteristics in western Washington. However, there are generally insufficient data available for determining when maximum concentrations of these pollutants can be expected.

Organic Pollutants

- Because of their low solubility in water, PAHs and many other organic compounds are strongly associated with sediments in highway runoff. Therefore, many of the factors that influence suspended solids in highway runoff will also apply to this category of pollutants.

- Few studies have been performed in western Washington to examine the specific factors influencing organic pollutant concentrations in highway runoff. In one study, organic compounds were shown to be correlated with TSS but not rainfall, ADT, or runoff volume.

- In other national studies, oil and grease concentrations were found to be strongly correlated with ADT. Furthermore, both oil and grease and TPH showed first flush behaviors. However, the extent to which these same patterns occur in western Washington is unclear given the regions unique precipitation patterns.

- There are little data available in western Washington for characterizing highway runoff concentrations for herbicides, pesticides, and PCBs. Therefore, no definitive conclusions can be made with regard to the prevalence of these pollutants in highway runoff.

- PAHs have only been measured at a few locations in western Washington. The five most commonly detected PAHs include pyrene, fluoranthene, phenanthrene, chrysene, and benzo(a)anthene.

- Because organic pollutants are generally associated with sediments, maximum concentrations for this category of pollutants can be expected to occur during high intensity rainfall events.

Bacteria

- Few studies have been implemented in western Washington to investigate factors influencing concentrations of bacteria in highway runoff. However, like many of the pollutants discussed above, bacteria are often associated with particles and sediments. Therefore, many of the factors that influence suspended solids in highway runoff will also apply to this category of pollutants.

- In general, fecal coliform bacteria concentrations for western Washington are higher than those from the national data. Because only limited data are available for *E. coli* and total coliform bacteria, their prevalence in highway runoff cannot be accurately assessed at this time.

Oxygen Demand

- Chemical oxygen demand is correlated with ADT during dry periods, whereas biological oxygen demand is correlated with ADT during both dry and wet periods.

- In western Washington, chemical oxygen demand was shown to be correlated with TSS.

- Chemical oxygen demand and biological oxygen demand are generally higher for western Washington than for the national data.

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APPENDIX A

Sites and Sources of Highway Runoff Data for Western Washington

Sites and Sources of Highway Runoff Data for Western Washington

Highway runoff data from western Washington was compiled from 35 sites. Most of the sites are located in the Seattle area, with two sites in Vancouver, Washington, and one site near Snoqualmie Pass. Table A-1 summarizes the data compiled for this report. Included in the table are details on the location of the sites, time period of the sampling, the number of events sampled, the parameters measured, the type of sample (event mean concentration [Flow-weighted Composite], grab), and the reference for the data. Of the 35 sites, 27 of them represent data collected from 1997 to the present. Only eight locations include data prior 1990.

Table A-1. Summary of studies used to characterize highway runoff in western Washington.

Location	Parameters	Sample Type	Sampling Period	Number of Storm Events	Reference
Interstate 5, milepost 96	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2003 to 2005	18	WSDOT 2006
Interstate 5, milepost 109	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2003 to 2004	9	WSDOT 2006
Interstate 5, milepost 122	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2004 to 2005	4	WSDOT 2006
Interstate 5, milepost 184	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness TPH-oil, TPH-diesel, fecal coliform	Flow-weighted Composite Grab	2005 to 2006 2005 to 2006	7 5	WSDOT 2006
Interstate 5, milepost 188	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2003 to 2004	12	WSDOT 2006
State Route 14 at SE 192nd Street	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness TPH-oil, TPH-diesel, fecal coliform	Flow-weighted Composite Grab	2005 to 2006 2005 to 2006	11 2,2,5	WSDOT 2006
State Route 18, milepost 8	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness TPH-oil, TPH-diesel, fecal coliform	Flow-weighted Composite Grab	2006 2005-2006	3 6	WSDOT 2006; Herrera 2007
State Route 18, milepost 13.3	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness TPH-oil, TPH-diesel, fecal coliform	Flow-weighted Composite Grab	2006 2006	4 6	WSDOT 2006; Herrera 2007
State Route 18, milepost 18	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness TPH-oil, TPH-diesel, fecal coliform	Flow-weighted Composite Grab	2006-2007 2006-2007	6 4	Herrera 2007
State Route 18, milepost 18.5	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness TPH-oil, TPH-diesel, fecal coliform	Flow-weighted Composite Grab	2006-2007 2006-2007	9 6	Herrera 2007

Table A-1 (continued). Summary of studies used to characterize highway runoff in western Washington.

Location	Parameters	Sample Type	Sampling Period	Number of Storm Events	Reference
State Route 18, milepost 20.3	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2006-2007	8	Herrera 2007
	TPH-oil, TPH-diesel, fecal coliform	Grab	2006-2007	6	
State Route 167, milepost 16	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2004 to 2005	16	WSDOT 2006
State Route 405, milepost 26	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2003 to 2004	5	WSDOT 2006
State Route 405, milepost 30	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2003 to 2005	23	WSDOT 2006
	Fecal coliform, *E. coli* bacteria	Grab	2005-2006	10	
State Route 500 at 112th Avenue	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2006	10	WSDOT 2006
	TPH-oil, TPH-diesel, fecal coliform	Grab	2006	2,2,3	
State Route 520 bridge (downspout data)	TSS, total metals (copper, lead, cadmium, antimony, arsenic, barium, chromium, cobalt, molybdenum, mercury, nickel, vanadium), total organic carbon, nitrate+nitrite, ammonia, orthophosphate-phosphorus, total nitrogen, total phosphorus, fecal coliform, *E. coli* bacteria, various PAHs and other organics, hardness	Flow-weighted Composite	2003 to 2004	3	King County 2006
State Route 522 at Bostain Road	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2005 to 2006	12	WSDOT 2006
	TPH-oil, TPH-diesel, fecal coliform	Grab	2005 to 2006	4,4,5	
State Route 525, milepost 1.4	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2005 to 2006	13	WSDOT 2006
	TPH-oil, TPH-diesel, fecal coliform	Grab	2005 to 2006	5	
State Route 525, milepost 2.5	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2005 to 2006	13	WSDOT 2006
	TPH-oil, TPH-diesel, fecal coliform	Grab	2005 to 2006	6	

Table A-1 (continued). Summary of studies used to characterize highway runoff in western Washington.

Location	Parameters	Sample Type	Sampling Period	Number of Storm Events	Reference
State Route 525, milepost 3	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2004 to 2005	13	WSDOT 2006
	Fecal coliform, *E. coli* bacteria	Grab	2005	8	
State Route 525, milepost 4	TSS, total copper, dissolved copper, total zinc, dissolved zinc, total phosphorus, hardness	Flow-weighted Composite	2004 to 2005	9	WSDOT 2006
State Route 520 bridge (bridge deck)	Total and dissolved zinc, total and dissolved copper	Grab	2005	4	Herrera 2005
Interstate 90 bridge (bridge deck)	Total and dissolved zinc, total and dissolved copper	Grab	2005	1	Herrera 2005
Hood Canal Bridge (bridge deck)	Total and dissolved zinc, total and dissolved copper	Grab	2005	2	Herrera 2005
Interstate 405 (I-405)	TSS, total zinc, dissolved zinc, orthophosphate phosphorus, total phosphorus, hardness, turbidity, pH	Flow-weighted Composite	2001 to 2002	11	Taylor 2002
Interstate 5 at Leverich Park; Vancouver, Washington	TSS, VSS, total and dissolved zinc, total and dissolved copper, total and dissolved lead, total cadmium, nitrate+nitrite, ammonia, total Kjeldahl nitrogen, orthophosphate-phosphorus, total phosphorus, various PAHs, chemical oxygen demand, alkalinity	Flow-weighted Composite	1997 to 1999	10	Yonge et al. 2002
NE Woodinville-Duvall Road near Redmond, Washington	TSS, total metals (copper, lead, zinc, cadmium, antimony, arsenic, barium, chromium, cobalt, molybdenum, nickel, vanadium), orthophosphate-phosphorus, total phosphorus, oil and grease, various organics, chemical oxygen demand, biological oxygen demand, hardness, alkalinity, turbidity, specific conductivity	Flow-weighted Composite	1995 to 1996	11	St. John and Horner 1997
State Route 12 in Montsano	TSS, VSS, total copper, total zinc, total lead, total organic carbon, nitrate+nitrite, total Kjeldahl nitrogen, orthophosphate-phosphorus	Flow-weighted Composite	1979 to 1980	27	Driscoll et al. 1990
State Route 520 in Seattle	TSS, VSS, total copper, total zinc, total lead, total organic carbon, nitrate+nitrite, total Kjeldahl nitrogen, orthophosphate-phosphorus	Flow-weighted Composite	1979 to 1980	43	Driscoll et al. 1990

Table A-1 (continued). Summary of studies used to characterize highway runoff in western Washington.

Location	Parameters	Sample Type	Sampling Period	Number of Storm Events	Reference
Interstate 90 at Snoqualmie Pass	TSS, VSS, total copper, total zinc, total lead, total organic carbon, nitrate+nitrite, total Kjeldahl nitrogen, orthophosphate-phosphorus	Flow-weighted Composite	1979 to 1980	12	Driscoll et al. 1990
Interstate 205 in Vancouver	TSS, VSS, total copper, total zinc, total lead, total organic carbon, nitrate+nitrite, total Kjeldahl nitrogen, orthophosphate-phosphorus	Flow-weighted Composite	1979 to 1980	61	Driscoll et al. 1990
Interstate 5 in Seattle	TSS, total lead, total nitrogen, total phosphorus, oil and grease, fecal coliform bacteria, chemical oxygen demand, biological oxygen demand	Flow-weighted Composite	1979 to 1980	54	Dalseg and Farris 1970
State Route 520	TSS, nitrate+nitrite, orthophosphate-phosphorus, total nitrogen, total phosphorus, oil and grease, total coliform bacteria, fecal coliform bacteria, chemical oxygen demand, alkalinity, turbidity, pH	Flow-weighted Composite	1972	4	Sylvester and DeWalle 1972
Interstate 5 @ NE 158th Street	TSS, VSS, total copper, dissolved copper, total zinc, dissolved zinc, total lead, dissolved lead, total organic carbon, nitrate+nitrite, orthophosphate-phosphorus, total phosphorus, total nitrogen, oil and grease, various organics, chemical oxygen demand, pH	Flow-weighted Composite	1979 to 1981	9	Zawlocki 1981; Portele 1981
State Route 520	TSS, VSS, total copper, dissolved copper, total zinc, dissolved zinc, total lead, dissolved lead, total organic carbon, nitrate+nitrite, orthophosphate-phosphorus, total phosphorus, total nitrogen, oil and grease, various organics, chemical oxygen demand, pH	Flow-weighted Composite	1979 to 1981	5	Zawlocki 1981; Portele 1981

APPENDIX B

Summary Statistics for Highway Runoff in Western Washington

Table B1. Summary statistics for highway runoff in western Washington.

Parameter	Number of Sites with Data	Average Percent Detected [a]	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Std. Dev	Interquartile Range [b]
Solids										
Total Suspended Solids (mg/L)	27	99.5%	118.9	93.0	2.7	294.6	60.4	190.7	82.5	130.3
Volatile Suspended Solids (mg/L)	5	100%	196.2	81.0	19.0	460.0	65.8	355.0	197.8	289.2
Metals										
Antimony, total (µg/l)	2	100%	4.93	4.93	1.16	8.70	1.16	8.70	5.33	7.54
Arsenic, total (µg/l)	2	100%	2.39	2.39	2.20	2.57	2.2	2.57	0.26	0.37
Barium, total (µg/l)	2	100%	82.4	82.4	80.8	84.0	80.8	84.0	2.26	3.20
Cadmium, total (µg/l)	3	100%	1.63	1.20	0.90	2.80	0.90	2.80	1.02	1.90
Chromium, total (µg/l)	2	100%	12.7	12.7	7.50	17.9	7.50	17.9	7.35	10.4
Cobalt, total (µg/l)	2	100%	3.15	3.15	1.90	4.40	1.90	4.40	1.76	2.5
Copper, total (µg/l)	29	98.3%	28.0	24.4	4.58	72.0	17.0	37.0	16.3	20.0
Copper, dissolved (µg/l)	21	99.0%	6.68	5.19	3.10	18.10	4.39	8.50	3.86	4.11
Lead, total (µg/l)	10	100%	296	120	24	1,065	46	451	345	405
Lead, dissolved (µg/l)	2	16.5%	2.10	2.10	1.00	3.20	1.00	3.20	1.56	2.2
Lead, total[c] (µg/l)	3	–	37.4	27.3	24	60.8	24	60.8	20.4	36.8
Lead, dissolved[c] (µg/l)	1	–	3.2	3.2	3.2	3.2	3.2	3.2	–	0
Mercury, total (µg/l)	1	100%	0.02	0.02	0.02	0.02	0.02	0.02	–	0
Molybdenum, total (µg/l)	2	100%	5.5	5.5	1.50	9.50	1.50	9.50	5.66	8.0
Nickel, total (µg/l)	2	100%	10.75	10.75	8.6	12.9	8.6	12.9	3.0	4.3
Vanadium, total (µg/l)	2	100%	10.54	10.54	6.28	14.8	6.28	14.8	6.0	8.5
Zinc, total (µg/l)	29	–	162	116	26.0	394	91.8	228	111	135
Zinc, dissolved (µg/l)	22	98.1%	48.24	39.04	13.00	133.94	23.30	69.30	34.33	46
Nutrients										
Ammonia nitrogen (mg/L)	2	100%	1.84	1.84	1.02	2.66	1.02	2.66	1.16	1.64
Nitrate+nitrite nitrogen (mg/L)	6	100%	1.53	1.54	0.51	2.99	0.72	1.89	0.89	1.17

Table B1 (continued). Summary statistics for highway runoff in western Washington.

Parameter	Number of Sites with Data	Average Percent Detected [a]	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Std. Dev	Interquartile Range [b]
Nutrients (continued)										
Total nitrogen (mg/L)	3	100%	9.66	6.50	0.78	21.7	0.78	21.7	10.8	20.9
Total Kjeldahl nitrogen (mg/L)	6	100%	1.17	0.77	0.38	3.40	0.60	1.09	1.12	0.49
Orthophosphate phosphorus (mg/L)	9	95.5%	0.13	0.10	0.01	0.42	0.03	0.17	0.14	0.13
Total phosphorus (mg/L)	24	98.6%	0.22	0.19	0.03	0.57	0.11	0.30	0.15	0.19
Organic Compounds – Petroleum Products										
Oil and grease, total (mg/L)	4	100%	71.5	43.5	11.8	187.0	27.4	115.5	78.5	88.1
Total petroleum hydrocarbon oil (mg/L)	12	100%	2.46	1.97	0.42	7.94	0.95	2.87	2.14	1.92
Total petroleum hydrocarbon diesel (mg/L)	8	38.6%	0.69	0.09	0.05	2.75	0.06	1.22	0.98	1.16
Organic Compounds – Miscellaneous										
2,4-Dimethylphenol (µg/l)	2	100%	0.39	0.39	0.25	0.54	0.25	0.54	0.21	0.29
Bis(2-Ethylhexyl)phthalate (µg/l)	1	100%	4.68	4.68	4.68	4.68	4.68	4.68	–	0
Benzyl alcohol (µg/l)	2	100%	0.86	0.86	0.59	1.13	0.59	1.13	0.38	0.54
2-Methylphenol (µg/l)	2	100%	0.81	0.81	0.59	1.03	0.59	1.03	0.31	0.44
4-Methylphenol (µg/l)	1	100%	2.04	2.04	2.04	2.04	2.04	2.04	–	0
Benzoic acid (µg/l)	2	100%	5.06	5.06	1.83	8.28	1.83	8.28	4.56	6.45
Benzyl butyl phthalate (µg/l)	2	100%	0.63	0.63	0.53	0.72	0.53	0.72	0.13	0.19
Di-n-butyl phthalate (µg/l)	2	100%	2.25	2.25	0.58	3.92	0.58	3.92	2.35	3.34
Di-n-octyl phthalate (µg/l)	2	100%	1.34	1.34	0.78	1.90	0.78	0.78	0.80	1.13
N-nitrosodiphenylamine (µg/l)	1	100%	0.62	0.62	0.62	0.62	0.62	0.62	–	0
Phenol (µg/l)	1	100%	3.02	3.02	3.02	3.02	3.02	3.02	–	0
2,4-Dinitrophenol (µg/l)	1	100%	0.69	0.69	0.69	0.69	0.69	0.69	–	0
4,6-Dinitro-o-cresol (µg/l)	1	100%	0.35	0.35	0.35	0.35	0.35	0.35	–	0
3-Methylphenol (µg/l)	1	100%	0.39	0.39	0.39	0.39	0.39	0.39	–	0
4-Nitrophenol (µg/l)	1	100%	2.03	2.03	2.03	2.03	2.03	2.03	–	0

Table B1 (continued). Summary statistics for highway runoff in western Washington.

Parameter	Number of Sites with Data	Average Percent Detected [a]	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Std. Dev	Interquartile Range [b]
Organic Compounds – Miscellaneous (continued)										
Bis(2-ethylhexyl)adipate (µg/l)	1	100%	0.78	0.78	0.78	0.78	0.78	0.78	–	0
Bisphenol A (µg/l)	1	100%	3.78	3.78	3.78	3.78	3.78	3.78	–	0
Caffeine (µg/l)	1	100%	1.33	1.33	1.33	1.33	1.33	1.33	–	0
Carbozole (µg/l)	1	100%	0.04	0.04	0.04	0.04	0.04	0.04	–	0
Total 4-Nonylphenol (µg/l)	1	100%	3.52	3.52	3.52	3.52	3.52	3.52	–	0
2-Methylnaphthalene	1	100%	0.06	0.06	0.06	0.06	0.06	0.06	–	0
Organic Compounds – PAHs										
Pyrene (µg/l)	3	–	0.36	0.35	0.34	0.39	0.34	0.39	0.05	0.03
Phenanthrene (µg/l)	2	63%	0.17	0.17	0.17	0.17	0.17	0.17	0.001	0.002
Fluoranthrene (µg/l)	3	–	0.30	0.30	0.27	0.33	0.27	0.33	0.03	0.06
Chrysene (µg/l)	3	75%	0.36	0.21	0.18	0.68	0.18	0.68	0.28	0.50
Benzo(a)anthracene (µg/l)	3	63%	0.24	0.16	0.12	0.45	0.12	0.45	0.18	0.33
Naphthalene (µg/l)	2	12.5%	0.10	0.10	0.06	0.14	0.06	0.14	0.06	0.08
Benzo(b)fluoranthene (µg/l)	2	12.5%	0.12	0.12	0.11	0.13	0.11	0.13	0.01	0.02
Benzo(g,h,i)perylene (µg/l)	3	12.5%	0.36	0.16	0.11	0.81	0.11	0.81	0.40	0.7
2-Methylnapthalene (µg/l)	2	50.0%	0.08	0.08	0.06	0.10	0.06	0.10	0.03	0.04
Organic Compounds – PAHs (continued)										
Anthracene (µg/l)	1	0.0%	0.10	0.10	0.10	0.10	0.10	0.10	–	0
Fluorene (µg/l)	1	0.0%	0.10	0.10	0.10	0.10	0.10	0.10	–	0
Benzo(k)fluoranthene (µg/l)	2	50.0%	0.09	0.09	0.08	0.10	0.08	0.10	0.02	0.02
Benzo(a)pyrene (µg/l)	2	50.0%	0.13	0.13	0.10	0.16	0.10	0.16	0.04	0.06
2-Chloronapthalene (µg/l)	1	0.0%	0.10	0.10	0.10	0.10	0.10	0.10	–	0
Acenapthylene (µg/l))	1	0.0%	0.10	0.10	0.10	0.10	0.10	0.10	–	0
Acenapthene (µg/l)	1	0.0%	0.10	0.10	0.10	0.10	0.10	0.10	–	0

Table B1 (continued). Summary statistics for highway runoff in western Washington.

Parameter	Number of Sites with Data	Average Percent Detected [a]	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Std. Dev	Interquartile Range [b]
Organic Compounds – PAHs (continued)										
Indeno(1,2,3-cd)pyrene (µg/l)	3	0.0%	0.34	0.15	0.10	0.76	0.10	0.76	0.36	0.66
Dibenz(a,h)anthracene (µg/l)	1	0.0%	0.10	0.10	0.10	0.10	0.10	0.10	–	0
Oxygen Demand										
BOD5 (mg/L)	2	100%	40.3	40.3	9.5	71.0	9.5	71.0	43.5	61.5
COD (mg/L)	11	100%	259.4	106.0	32.0	1,377.0	46.0	227.0	399.1	181.0
Bacteria										
Fecal Coliform Bacteria (CFU/100mL)	16	100%	1,763	892	35	11,775	306	1,790	2,849	1,484
Total Coliform Bacteria (CFU/100mL)	1	100%	9,350	9,350	9,350	9,350	9,350	9,350	–	0
Total E. Coli (CFU/100mL)	3	100%	784	551	130	1,670	130	1,670	796	1,540
Conventionals										
Alkalinity (mg/L as $CaCO_3$)	2	100%	21.4	21.4	19.3	23.4	19.3	23.4	2.9	4.1
Hardness (mg/L as $CaCO_3$)	19	100%	35.7	28.9	11.1	86.1	19.4	49.6	20.7	30.2
Total organic carbon (mg/L)	8	100%	32.8	21.0	2.0	139.0	5.0	34.5	45.0	29.5
Turbidity (NTU)	3	100%	62.5	84.4	16.3	86.7	16.3	86.7	40.0	70.4
pH	5	100%	6.4	6.6	5.8	6.8	6.0	6.8	0.5	0.8
Specific Conductivity (µS/cm)	1	100%	71.6	71.6	71.6	71.6	71.6	71.6	–	0

[a] The percentage of time the measured parameter was detected averaged over all sites reporting data.
[b] The interquartile range is the 75^{th} percentile minus the 25^{th} percentile.
[c] This lead data only includes data post 1990 to represent runoff not influenced by leaded gasoline
PAH – polycyclic aromatic hydrocarbons.
CFU – colony forming units.
µg/l – micrograms per liter.
mg/l – milligrams per liter.